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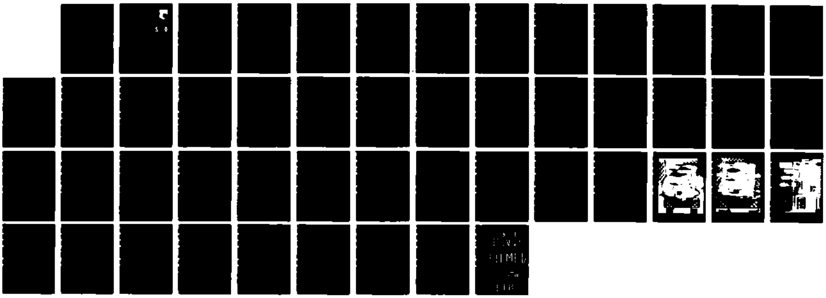

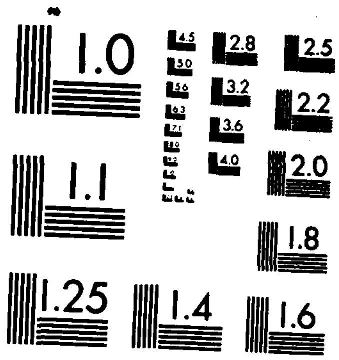

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AFWAL-TR-85-2084

LONG-LIFE, REPETITIVE-PULSE SWITCH FOR LASERS

D. Turnquist

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DECEMBER 1985

FINAL REPORT FOR PERIOD SEPTEMBER 1982 - JUNE 1985

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This program is the first phase of the development of a scalable, long-life, high pressure, closing switch for use in repetitively-pulsed high voltage systems. The objectives were to develop a conceptual switch design and to perform experiments to establish the feasibility of the switch for varying voltage/pulse life. To fulfill the requirements a switch was conceived with the features of: a high pressure gas fill, for high voltage holdoff and fast current rise; a discharge formation control scheme to generate a uniform discharge that will minimize filamentation and arcing; a deionization electrode system to allow operation at typical laser repetition rates; a linear (50-100 cm length) geometry compatible with transverse-discharge lasers. The first part of this program was directed toward delineation of the important switch design parameters and toward the design of the experimental switch. Areas reviewed for the first part were uniform discharge growth at high pressure, basic data for the gases under consideration, and preionization ion density requirements. For the second part of the program an experimental device was built and experiments were run to determine the switch characteristics.

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1. INTRODUCTION

This program is the first phase of the development of a scalable, long life, high pressure, closing switch for use in repetitively pulsed high voltage systems. The first phase objectives were to:

1) Develop a conceptual switch design.

2) Perform experiments to establish the feasibility of the switch.

The switch performance objectives were:

Voltage Hold Off	60 kV
Peak Current	100 kA
Current Rise Time	10 usec
Pulse Repetition Rate	1000 Hz
Pulse Width	50 to 200 nsec
Operating Life	5000 Hrs
Switching Loss	<20%

In order to fulfill these requirements a switch was conceived with the following novel features.

1) A high pressure gas fill, for high voltage holdoff and fast current rise.

2) A discharge formation control scheme to generate a uniform discharge that will minimize filamentation and arcing, utilizing:

   a) a long-life, low temperature, non-arcing cathode material,
   b) intense preionization,
   c) a fast-rising trigger pulse,

3) A deionization electrode system, to allow operation at typical laser repetition rates, and

4) A linear (50 - 100 cm. length) geometry compatible with transverse-discharge lasers.

The first part of this program was directed toward delineation of the important switch design parameters and toward the design of the experimental switch.

For this purpose, the theory pertaining to uniform discharge growth at high pressures was reviewed, along with the necessary basic data for the gases under consideration, and preionization ion density requirements were calculated.

Calculations were also done to determine the efficacy of using 50 to 100 kV X-rays to produce the pre-ionization.

In the second part of the program an experimental device was built, and experiments were run to determine the switch characteristics.

2. DESIGN APPROACH

2.1 Design Concept

The switch concept under investigation was based on obtaining

1) The combination of the high voltage holdoff and rapid switching at high pressures, as in spark gaps,

2) Electron emission from an active cathode, without the destructive effects of arcing, and

3) A diffuse, uniform, controlled conduction channel, without high impedance filamentation or discharge localization.

The first two of these are accomplished by the use of a reducing or inert gas at pressure - electrode spacing products typical of high-pressure switching devices, of the order of 5 atmosphere-cm., and by the use of an impregnated tungsten cathode.

2.2 Cathode

The thermionic emitter cathode provides a uniform source of electrons, without the irregularities that can precipitate discharge filamentation. Recent experiments with these catnodes in low pressure hydrogen, and an extensive operating history in high pressure devices (xenon flash lamps, e.g.) show that the required emission current densities of 300 to 1000 amps/cm can be achieved at temperatures of several hundred degrees C. Cathode temperatures of this order are often reached by self heating of the electrodes in repetitive discharges.

Cold cathode devices using the same material have also been successful in two very different switching devices.

One of these is the instant start thyratron program conducted by ERADCOM and AFWAL (WPAFB). The cold cathode program was carried on for several years, starting with the low power "Plasma Heated Thyratrons" (4), continuing to scaling to higher power standard thyratron levels at several thousand amps peak (5), and to megawatt average power levels at 10's of kA (6). All of these programs were successful, with a succession of designs at increasing power levels. None of the designs failed. The last tube of this series ran well initially, was unused for some 2 years, but then re-conditioned and run again at megawatt levels at ERADCOM.

The cathode material used is the same type of material which has already seen extensive service in large metal-envelope tubes, such as those used for long life induction heating service. These tungsten matrix/barium aluminate cathodes are being tested at high current densities, and may be readily manufactured in shapes which lend themselves well to low inductance, high peak current, and high rms current duty.

There are still many unknown factors.

1) The emission mechanism at low temperatures in hydrogen, where these cathodes emit copiously, is not know. There is some reason to believe that the appropriate mechanism is field emission from needle-like crystals of Barium Aluminate. Indeed, that seems to be the only likely mechanism for emission at so low a temperature.

2) Partly as a result, the heat dissipation and current distribution as a function of current and time is also unknown.

3 It is known that the cathode can operate for 10's or hundreds of hours continuously if it is able to reach temperatures of a few hundred degrees. Five or six hundred seems to be about the optimum temperature. The limits are not known.

4) There has not yet been enough testing to establish long term life, or life under conditions of short bursts or intermittent operation.

5) The cathode has been sometimes very difficult to activate, both new and after a period of abusive testing. The limits for activation or re-activation under various conditions are not known.

6) The chemical interactions of the cathode with the gas and with the tube materials are not known. That some important effects are present is known from difficulties encountered with the reservoir in some experimental thyratrons.

In spite of these difficulties, it has been possible to design thyratrons to predetermined specifications, and to achieve usable life. The most recently developed cold-cathode tube has been a megawatt average power tube.

Life has, in each case, involved substantial abuse and arcing of the cathode during the experimental testing. Autopsied tubes, however, have shown little sign of wear or damage. Most test were terminated without cathode failure.

Another type of device is not so well known, but is a series of commercial over-voltage gaps used in certain aircraft applications. These small devices switch energies of several joules with a Hydrogen-Argon fill gas at about 1/3 atmosphere. The same impregnated tungsten matrix cathode material is used, operated cold at several hundred amps/cm^2. The devices are noted for their unusual stability and life -- less than 10% breakdown voltage variation over a 300,000 coulomb life span.

2.3 Pre-Ionization

To obtain uniform discharge growth the concept is based on techniques and theories developed for transverse discharge lasers, using intense preionization and rapidly rising electric fields.

A detailed treatment of this problem has been published by Levatter and Lin (1), who considered the requirements for formation of homogeneous discharges with finite voltage rise times.

Using the results of numerical solutions to the Boltzmann equation of a He-Xe-F2 mixture as an example, they calculate the required preionization density as a function of voltage rise time. Using this approach, Ramrus and Pereira (2) have analyzed a proposed model for a preionized high pressure multi-channel arcing switch, with an electron attaching gas fill mixture. A literature search also found a treatment by Herziger, Welermann-Windgasse and Banse. Here preionization requirements are derived for the general case, with calculations for a number of gases and a comparison with results for argon. This treatment neglects the finite voltage rise time, however, and thus may considerably overestimate the actual preionization requirements. Both theories require the use of either electron swarm energy (D/u) or electron energy-loss-per-collision data, neither of which are known with any certainty for the conditions of interest here.

In spite of the errors introduced by these uncertainties as well as by the simplifying assumptions of the theories, they have been shown to give results in reasonable agreement with experiments. We have therefore used both theories to calculate preionization levels for gases of interest to this program, as described in section 3.2.1.

3. EXPERIMENTAL SWITCH DESIGN

3.1 Gas Composition

The choice of gas for the switch is dependent on several factors.

1. Compatibility with the cathode requires the use of a reducing or inert gas. Small admixtures of an electron attaching gas may be possible, as indicated by some experiments, but are undesirable in that they reduce cathode activity.

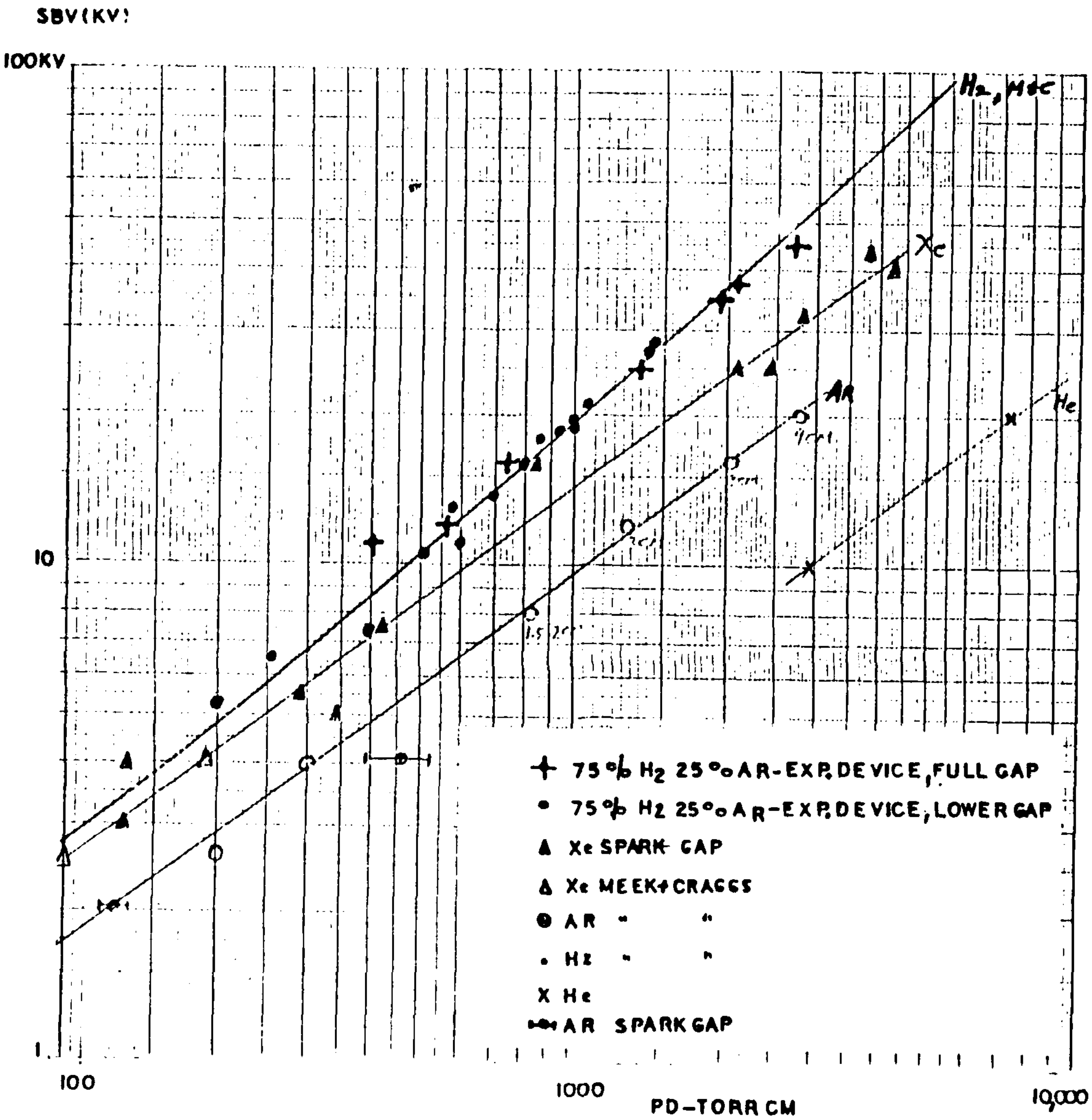
2. Holdoff voltages of at least 70 kV should be obtained at reasonable Pd (Pressure x spacing) values, no more than 6 or 7 atm-cm. Larger Pd requirements would tend to produce either long switches with higher inductance and more difficult production of uniform preionization, or shorter switches with a very high internal pressure and consequent mechanical problems.

3. Rapid deionization rate, and hence high attachment and/or recombination rates.

4. Pre-ionization is required, and hence a large ionization cross section with UV or X-rays.

Static holdoff voltage for several gases of interest are shown in Figure 1. Of the possibilities, hydrogen with a high holdoff and a finite attachment coefficient is the first choice, with argon or argon-hydrogen mixtures as alternatives. Little data seems to be available on the later combination, but H2 additives to both Xe and He are known to increase holdoff and decrease deionization time.

The pre-ionization makes the H2-Ar mixture preferred, since hydrogen has relatively little interaction with either UV or X-rays produced at reasonable intensities. As a result of these considerations as well as results on smaller commercial devices, a gas composition of 75% hydrogen and 25% Argon was chosen for these experiments.



— FIGURE I —
STATIC BREAKDOWN VOLTAGE

3.2 Pre-Ionization

3.2.1 Pre-Ionization Requirements

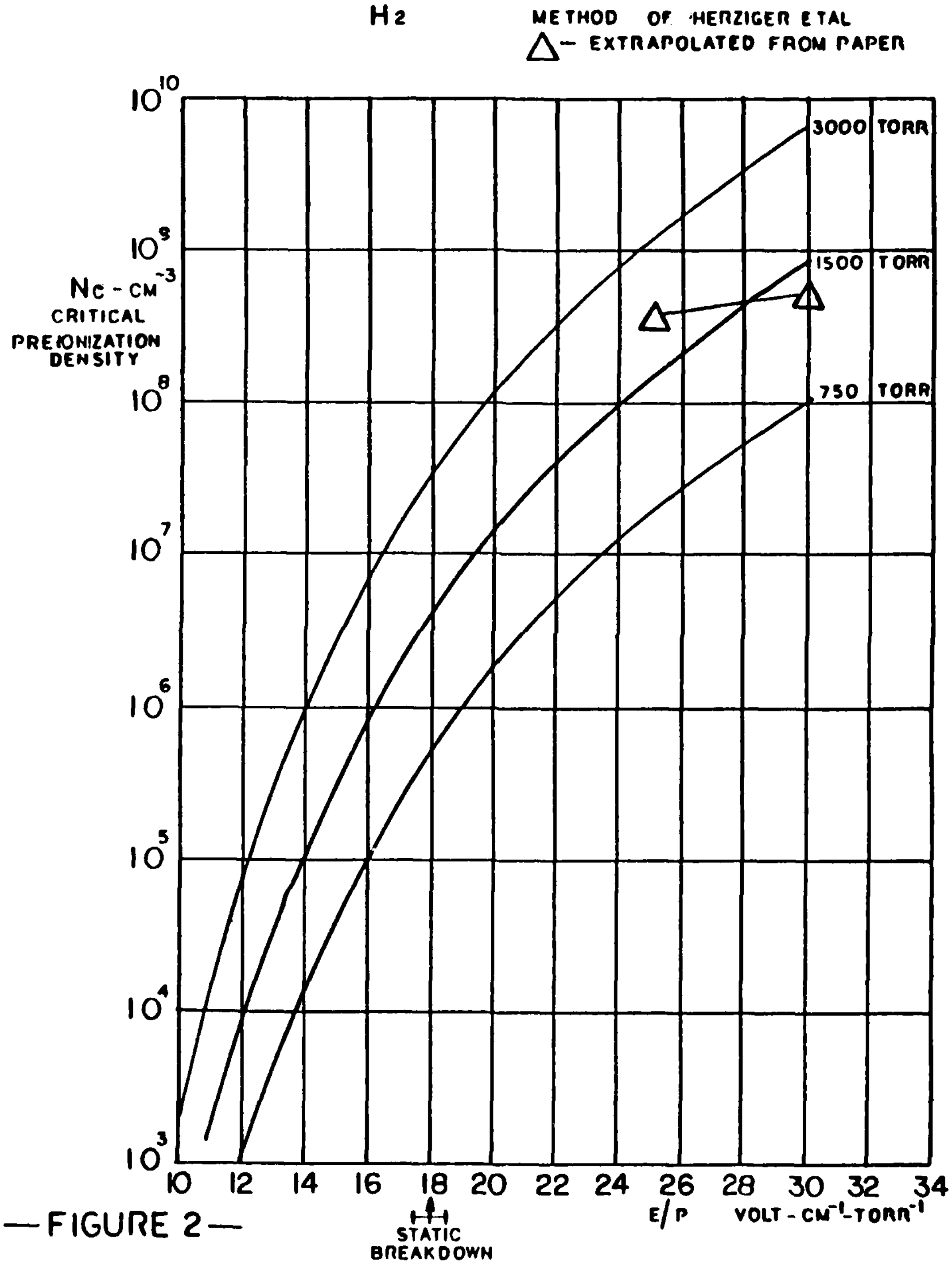
Two methods were used to compute pre-ionization requirements. The theory of Herziger, et al, yields a fairly simple expression; the results for hydrogen are shown in Figure 2. It was not possible to exactly recompute these results using the information given in the paper. We used instead expressions for ionization growth, collisional energy loss, and mean free path derived from data in the usual reference books on atomic and molecular collisions and plasma data. (These references include Bates, Brown, McDaniel, Massey and Burhop, and Von Engel in Handbuch der Physik.)

At E/P values of 25 to 30 V/cm/Torr the agreement is not too bad, but at higher E/P our results diverge significantly from those of Herziger. The difference is very likely due to the difficulties encountered with the electron swarm energy, as shown in Figure 3. We used data from Brown, McDaniels, and at high E/P, from Saelee and Lucas. In any case these densities are significantly higher than those predicted using the more difficult expressions of Levatter and Lin.

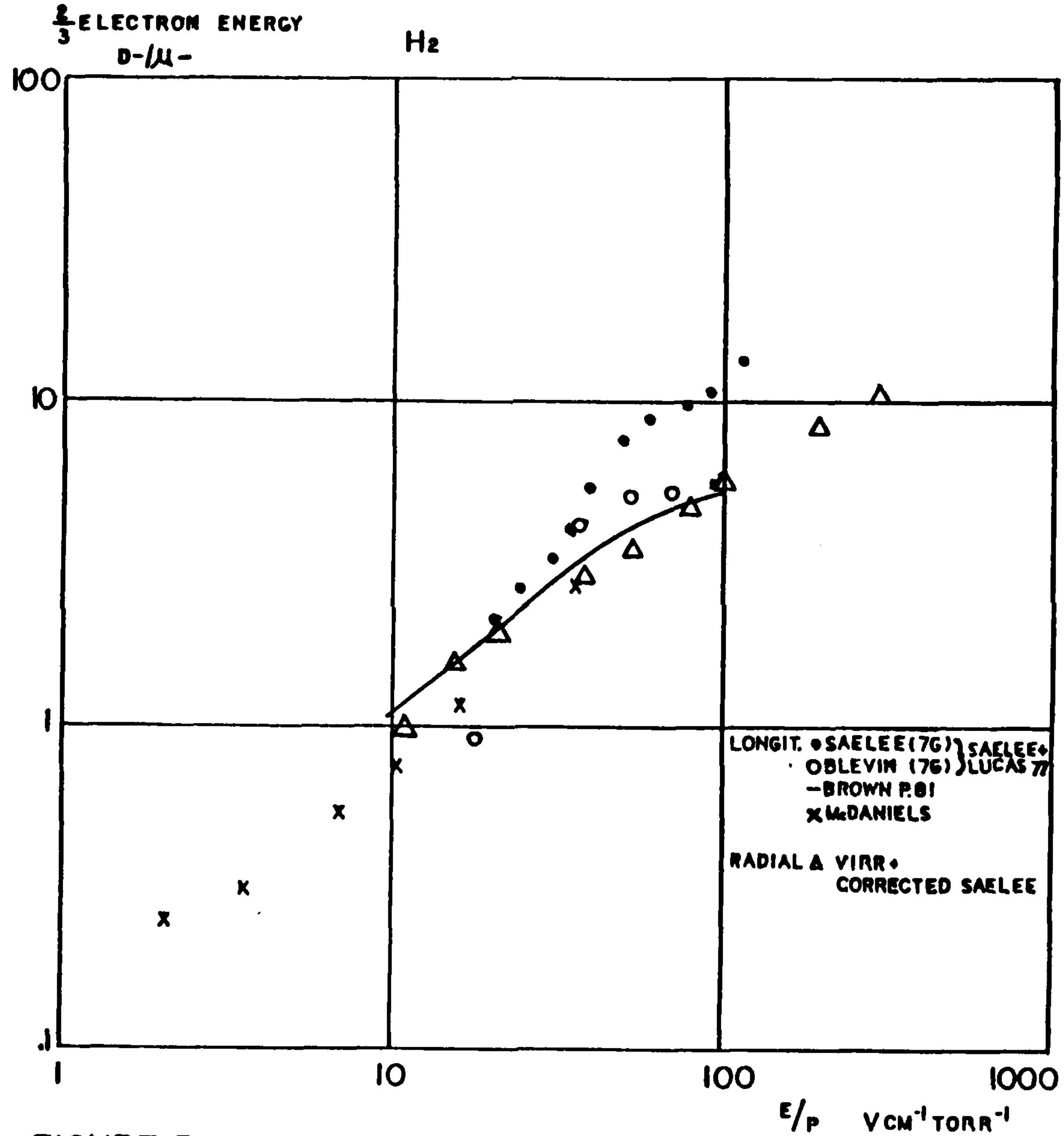
The final results of a series of calculations (done also for H2) are shown in Figure 4, in the form of critical density versus voltage rise time, for the same pressures as in Figure 3. As is seen here, the preionization requirement drops almost inversely with rise time. The upper limit of rise time is caused by the development of Townsend breakdown, as opposed to the desired development of multiple, current-spreading discharge features. This limit generally occurs in the order of a microsecond. The lower limit is due to our ability to generate fast rising pulses without undue difficulties.

From the consideration above, we have established the following operating parameters for the switch:

1.	Main Electrode Spacing	2-3 cm	
2.	Fill Gas - choice - alternatives	Hydrogen - Argon Ar, H2, or mixtures	
3.	Pressure	100 - 3000	Torr
4.	Pressure x distance (Pd)	200 - 4000	Torr-cm
5.	Preionization density	10 - 10	ions/cm
6.	Switch Operating E/P	5 - 17	V/cm/Torr
7.	Trigger E/P	15 - 35	V/cm/Torr
8.	Trigger rise time	10 - 100	ns.

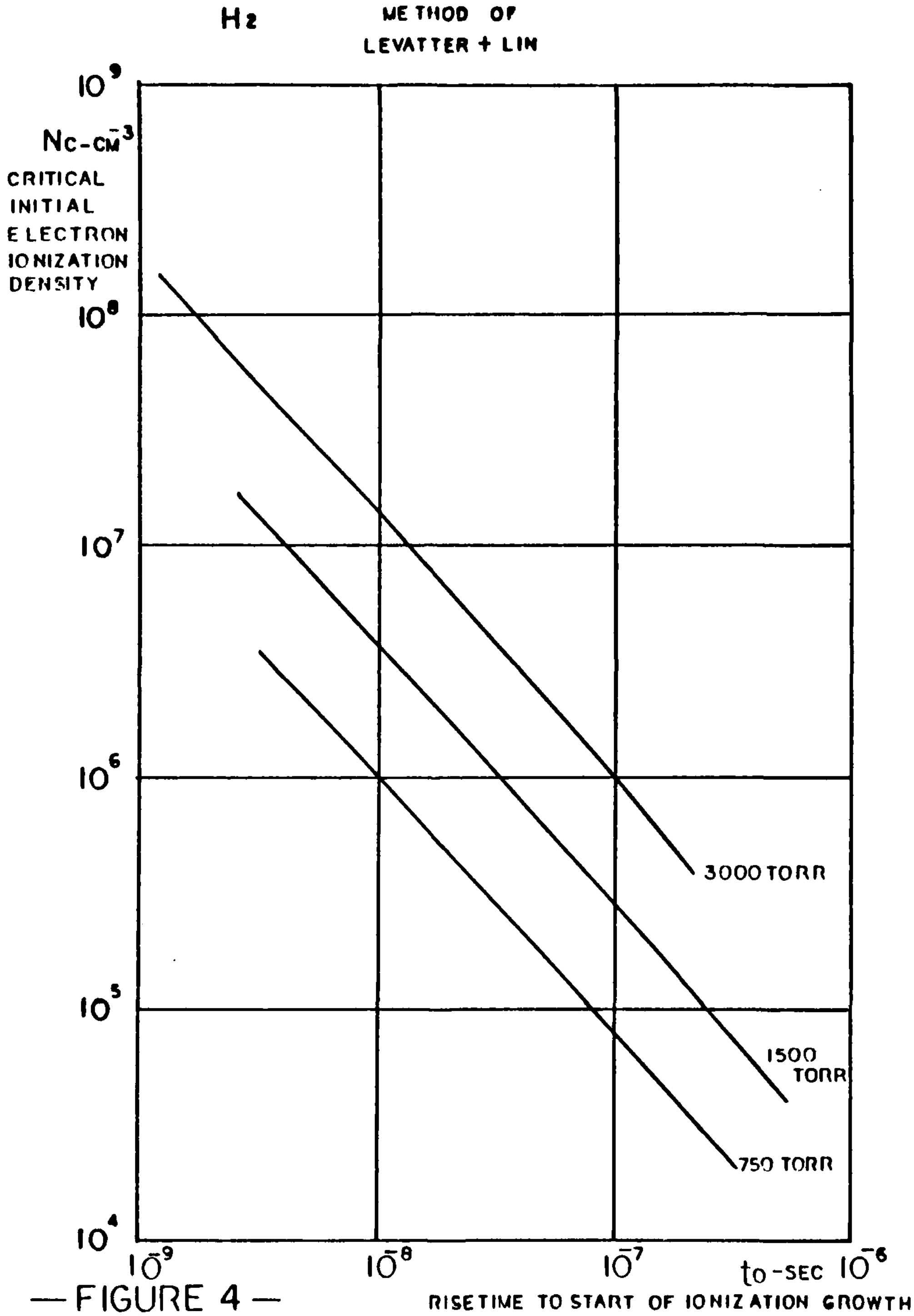

H2
METHOD OF HERZIGER ET AL
△ — EXTRAPOLATED FROM PAPER
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
Nc - CM^-3
CRITICAL
PREIONIZATION
DENSITY
3000 TORR
1500 TORR
750 TORR
10
12
14
16
18
20
22
24
26
28
30
32
34
STATIC
BREAKDOWN
E/P VOLT - CM^-1-TORR^-1

— FIGURE 2 —



—FIGURE 3—

ELECTRON ENERGY


H2
METHOD OF
LEVATTER + LIN
10^9
N_c-cm^{-3}
CRITICAL
INITIAL
ELECTRON
IONIZATION
DENSITY
10^8
10^7
10^6
10^5
10^4
3000 TORR
1500
TORR
750 TORR
10^{-9}
10^{-8}
10^{-7}
t_0-sec 10^{-6}
RISETIME TO START OF IONIZATION GROWTH

— FIGURE 4 —

3.2.2 X-Ray Source Calculation

In order to produce a well defined source of ionization, it was originally planned to use X-rays, with a generator operating between 50 and 100 k V. A theoretical calculation was done to predict the efficiency and the voltage and current requirements for such a device. It was assumed that the X-ray source - a long, narrow thermionic cathode and a target anode would be mounted in a vacuum chamber adjacent to the switch. The X-rays produced by electron bombardment of the anode would be allowed to pass through a thin Be or Ad window into the switch so as to ionize most of the active volume of the switch. The results of the analysis are summarized below.

<u>Efficiency of X-ray Production at a target</u>

From a formula due to Kilpatrick (ref. 8, p. 14)

The power efficiency of x-ray production, i.e., the power of the x-ray beam divided by the power of the electron beam is given by

$$\text{eff} = 1.4 \times 10^{-9}\ 10\ ZV$$

where Z = target atomic number

V = beam voltage

	Molybdenum Z = 42	Tungsten Z = 74
<u>KV</u>	<u>efficiency</u>	<u>efficiency</u>
10	.059%	.104%
20	.118	.207
40	.235	.414
60	.35	.62
80	.47	.83
100	.59	1.049

The Angular Distribution of X-Rays

For a non-relativistic beam the intensity I = KV I for a thin target is given by

$$I = \frac{|a|\ e^2 (v/c)}{4 \pi r^2 C^2} \sin^2\theta$$

where:

- a = constant, deceleration in target of incident electrons -cm/sec
- e = electron charge - esu
- n = distance of observation - cm
- c = vel. of light - cm/sec
- θ = Angle with respect to the electron beam

An equation for x-ray production vs. angle at a thick target was not found. However, all the comments found on actual x-ray tubes suggest an optimal angle of x-ray output at 90 degrees to the electron beam (9). The anode tilt angle is often 70 degrees to the beam to maximize the X-ray production. For our purposes, we used a cosine squared pattern. It was further assumed that the 1 cm wide target was 5 cm away from the window aperture, of 1 cm, into the switch. The volume of gas to be irradiated was about 5 cm deep, by 1 cm wide. The X-ray source length was the same as the switch length. (For the experiment, the length was 0.1 meter). Using what is, then, an effective useful angle from the X-ray source of 3.814 degrees, we find that about 8.5% of the X-rays produced would enter the useful, active gas chamber area of the switch.

Effective Energy of the X-ray Spectrum

The X-ray spectrum produced off a thick target is a continuum with a maximum X-ray energy in electron volts given by the accelerating potential of the cathode rays to the target.

Sometimes it is desirable to represent a polychromatic spectrum by an "equivalent" effective monochromatic energy beam. This has often been researched in CAT Scanner analyses. Typical valves found were (7):

Accelerating Potential	Effective Energy
100KV	62Kev
120KV	72Kev
140KV	79Kev

or a ball park figure is to assume:

Effective Energy = 2/3 tube potential (or 6/10)

Consequently, we assume tube potentials of:

15 30 60 75 90 and 120 KV

To give monochromatic equivalences of:

10 20 40 50 60 and 80 Kev

Beryllium Window

The X-rays entering the gas chamber will be partially absorbed during passage through a beryllium window of .010" thickness (=.0254cm). The fraction of X-rays transmitted through the window follows Beers Law

$$I = I_o \exp(-\mu x)$$

where

I_o = incident intensity
e = 2.718
m = linear attenuation coefficient in cm
x = thickness of absorber in cm.

M is a function of material and photon energy.

For 0.010" (0.0254 cm) beryllium we have (10):

Energy (Kev)	M (cm-1)	exp(-μx)
10	1.097	.9725
20	.420	.989
40	.305	.992
50	.289	.9927
60	.278	.9930
80	.259	.9934

Energy Absorbed in the Gas Chamber

Because we are dealing with gases it will be useful to use μ/p - the most attenuation coefficient - which differs from the linear attenuation coefficient as it has been divided by the density (hence μ/p has units of cm^2/gm). The values listed below are at STP; to consider gases at K atmospheres, multiply the density p by k when obtaining $\mu = (\mu/p)p$.

The mass energy coefficient μ_{en}/p indicates how much of the scattered or deflected photon energy results in direct energy absorption at the scattering site and will be useful for calculation of gas ionization.

A sample calculation for a thickness x has:

transmitted intensity $I = I_o \exp(-ux)$

"scattered" intensity $= Io\,[1 - \exp(-\mu x)]$

absorbed energy $= \dfrac{(\mu_{en}/p)}{(\mu/p)} I_o [1 - \exp(-\mu x)]$

(with conversion of I_o to [# photon x Energy/photon] in the last equation)

Because of the very low absorption by hydrogen, the two gases of interest were Argon (Z = 18) and Xenon (Z = 54). Because no table of μ, μ/p, or μ_{en}/p for Xenon were available, a rough approximation was formed by using μ of Iodine (Z = 53) and $(\mu_{en}/p)/(\mu/p)$ from tables on Tin (Z = 50).

Because Iodine is lower in atomic number than Xenon it is assumed that its μ's are an underestimate, however, as μ_{en}/p decreases with increasing Z, Tin's valves are assumed to be an overestimate. Consequently its hoped that the two values, when combined, partially compensate.

Densities for Hydrogen, Argon, and Xenon at STP are:

H	.000099 gm/cc
Ar	.001784 gm/cc
Xe	.005896 gm/cc

We then find:

	Argon (Z = 18)				Xenon (Z = 54)		
					(Iodine)	(Tin)	
E (KeV)	μ/p	μ_{en}/p	μ_{en}/μ	μ/atom [cm−1]	μ/p	μ_{en}/μ	μ/atmos [cm−1]
10	64.5	62.3	0.966	0.111	161.	0.965	0.949
20	8.53	8.02	0.940	0.0152	26.0	0.930	0.153
30	2.62	2.31	0.882	0.00467	8.67	0.392	0.0511
40	1.20	0.962	0.802	0.00214	* 22.7	0.513	0.134
50	0.687	0.488	0.710	0.00123	12.6	0.582	0.0743
60	0.460	0.284	0.617	0.00082	7.78	0.642	0.0459
80	0.275	0.128	0.466	0.00049	3.65	0.722	0.0215
100	0.024	0.0735	0.360	0.000364	2.00	0.744	0.0118

*Iodine has a K-shell edge at 33.166 KeV, Xenon is at 34.59 KeV; This sudden jump is due to photoelectric absorption.

The next calculation is the fraction entering the gas chamber that is converted to ionization energy; it will be assumed equal to:

$$[1 - \exp(-\mu x)]\mu_{en}/\mu$$

with x = 5 cm and for values of 1,2,3,4, and 5 atmospheres of gas pressure.

Useful (ionizing) fraction of energy absorbed, of the energy going into the switch chamber

ARGON

E	1ATM	2ATM	3ATM	4ATM	5ATM
10	.411	.648	.783	.861	.906
20	.0688	.133	.192	.246	.297
30	.0204	.0402	.0597	.0786	.0972
40	.00854	.0170	.0253	.0336	.0418
50	.00435	.00868	.0130	.0173	.0215
60	.00252	.00504	.00754	.0100	.0125
80	.00114	.00228	.00341	.00455	.00567
100	.000655	.00131	.00196	.00261	.00326

XENON

E	1ATM	2ATM	3ATM	4ATM	5ATM
10	.957	.965	.965	.965	.965
20	.497	.729	.836	.886	.910
30	.0884	.157	.210	.251	.283
40	.251	.379	.444	.478	.495
50	.181	.306	.392	.451	.492
60	.132	.236	.320	.386	.438
80	.0736	.140	.199	.252	.300
100	.0426	.0828	.121	.156	.190

Energy into the Target

It is assumed that a 1 microsecond pulse of current up to 1 ampere and within the range of 0 to 100 kilovolts can strike the target.

as 1 Watt = 1 Joule/sec

The maximum energy available is $(10^{-6}\text{ sec})(10^{5}\text{ volts})(1\text{amp}) = 0.1$ joule

and 1 Joule = 6.242×10^{18} eV

We can get 6.24×10^{17} eV out of out power supply (@ 100 kV)

We can generate a table indicating the amount of X-ray energy going into the gas chamber by combining the target efficiency, and assuming a (worst case) 8.5% fraction goes in due to the 5 cm value of A.

Energy into Gas Chamber

E (kev)	Molybdenum Target	Tungsten Target
10	3.13×10^{12} eV	5.51×10^{12} eV
15	7.02×10^{12}	1.24×10^{13}
20	1.25×10^{13}	$2\ 21 \times 10^{13}$
30	1.87×10^{13}	3.30×10^{13}
40	4.98×10^{13}	8.78×10^{13}
45	6.32×10^{14}	1.11×10^{14}
50	4.98×10^{14}	1.37×10^{14}
60	1.11×10^{14}	1.96×10^{14}
75	1.75×10^{14}	3.08×10^{14}
80	2.0×10^{14}	3.52×10^{14}
90	2.53×10^{14}	4.45×10^{14}
100	3.13×10^{14}	5.51×10^{14}
120	4.49×10^{14}	7.91×10^{14}

Ionization Energy of Argon, Xenon

The ionization energy for air is about 33 eV and for Argon 29 eV (9). Comparison using a Handbook of Chemistry and Physics suggests that the energy for Xenon will be considerably less than either of these.

Ionization Potentials

	I	II	III
A	15.68	27.76	40.75
N	14.48	29.47	47.40
O	13.55	34.93	54.87
Xe	12.08	(21.1 ?)	32.0

As a ball park figure we will use 30 eV as the necessary energy to ionize Argon or Xenon.

Assume the gas chamber has a volume $1 \times 5 \times 10$ cc = 50 cc

Suppose our goal is to produce 10^7 ions per cc.

This corresponds to a net absorbed ionization energy of

$50\text{cc} \times 10^7$ ions/cc $\times$ 30 eV/ion = 1.5×10^{10} eV

We can take the ratio of 1.5×10^{10} eV to the energy (in eV) going into the gas chamber to establish the minimal permissible fraction of absorbed energy needed and compare it to the table to see if the criterion is met.

$$\text{Minimum fraction necessary} = \frac{\text{Total E to Produce } 10^{7} \text{ ions/cc}}{\text{Energy Entering Gas Chamber}}$$

Compare with ionizing Fraction:

E(kev)	Mo Target	W Target
10	4.8×10^{-3}	7.72×10^{-3}
15	2.14×10^{-3}	1.2×10^{-3}
20	1.2×10^{-3}	6.79×10^{-4}
30	8.02×10^{-4}	4.55×10^{-4}
45	2.37×10^{-4}	1.35×10^{-4}
60	1.35×10^{-4}	7.65×10^{-5}
75	8.57×10^{-5}	4.87×10^{-5}
90	5.92×10^{-5}	3.37×10^{-5}
120	3.34×10^{-5}	1.90×10^{-5}

All cases seem to be surpassed:

E(KeV)	Mo Target	W Target
40	3.01×10^{-4}	1.708×10^{-4}
50	1.92×10^{-4}	1.095×10^{-4}
80	7.5×10^{-5}	4.26×10^{-5}
100	4.79×10^{-5}	2.72×10^{-5}

Ratio of Expected/Necessary Energy Deposit for Ionization all at 1 amp beam current:

ARGON

	Mo Target					W Target				
E	1A	2A	3A	4A	5A	1A	2A	3A	4A	5A
10	85.6	135	163	179	189	151	236	288	317	333
20	57.3	111	160	205	248	101	196	283	363	437
30	25	50	74	98	121	44.8	88.4	131	173	214
40	28	56	84	112	139	50	100	148	197	245
50	22.7	45	68	90	112	40	79	119	158	196
60	18.7	37	57	74	93	32.9	65.9	98.6	131	163
80	15.2	30	45	61	76	26.8	54	80	107	133
100	13.7	27	41	55	68	24	48	72	96	120

XENON

	Mo Target					W Target				
E	1A	2A	3A	4A	5A	1A	2A	3A	4A	5A
10	199	201	201	201	201	352	355	355	355	355
20	414	608	697	738	758	732	1074	1230	1305	1340
30	120	196	262	313	353	194	345	462	552	622
40	834	1260	1475	1590	1645	1470	2220	2600	2800	2900
50	943	1590	2040	2350	2560	1650	2795	3580	4120	4495
60	977	1750	2370	2860	3240	1725	3085	4185	5045	5725
80	981	1865	2655	3360	4000	1728	3290	4670	5915	7040
100	889	1730	2525	3255	3965	1577	3044	4450	5735	6985

3.3 Experimental Design

3.3.1 Basic Design

The cathode for the experimental switch is a planar surface 1-1/2 cm. x 10 cm., with an indirect heater embedded in the tungsten cathode block.

Two anode arrangements were used. Several requirements had to be met:

1) The electric field during triggering should be reasonably uniform, without regions of low field (and greatly diminished growth in numbers of ions) or very high fields (leading to uncontrollably rapid growth and discharge filamentation.)

2) The electrodes and support structure must allow reasonable "illumination" by the preionization source.

3) The electrodes must be of a size which will allow accidental faults and arcs to occur without damage.

4) The anode, trigger electrode, and bias electrode structures must be arranged to minimize the probability of unwanted trigger arcing.

To optimize the electrode field configurations we used a simple field plotting technique.

The overall structure is completely demountable, using a flange and glass cylinder configuration with L seals for the upper structure.

We had planned to use X-rays at less than 100 kV as the preionization source. The X-ray generator is integrated into the main switch structure and a cathode of the same design as that of the main switch is used in the electron source. (X-rays are preferred over other sources of preionization as being a better controlled and better defined source than the common spark generator UV sources used in many lasers.)

The critical parameters for the switch experiment are:

Parameter	Effect
Pre-Ionization Level	Uniform Discharge Formation
Trigger Voltage Rise Time	Uniform Discharge Formation
Electric Field Configuration	Uniform Discharge Formation
Gas Composition	Holdoff Voltage Cathode Compatability Rapid Deionization
Cathode Emission	Uniform Discharge Formation Life

3.3.2 Electrode Geometry

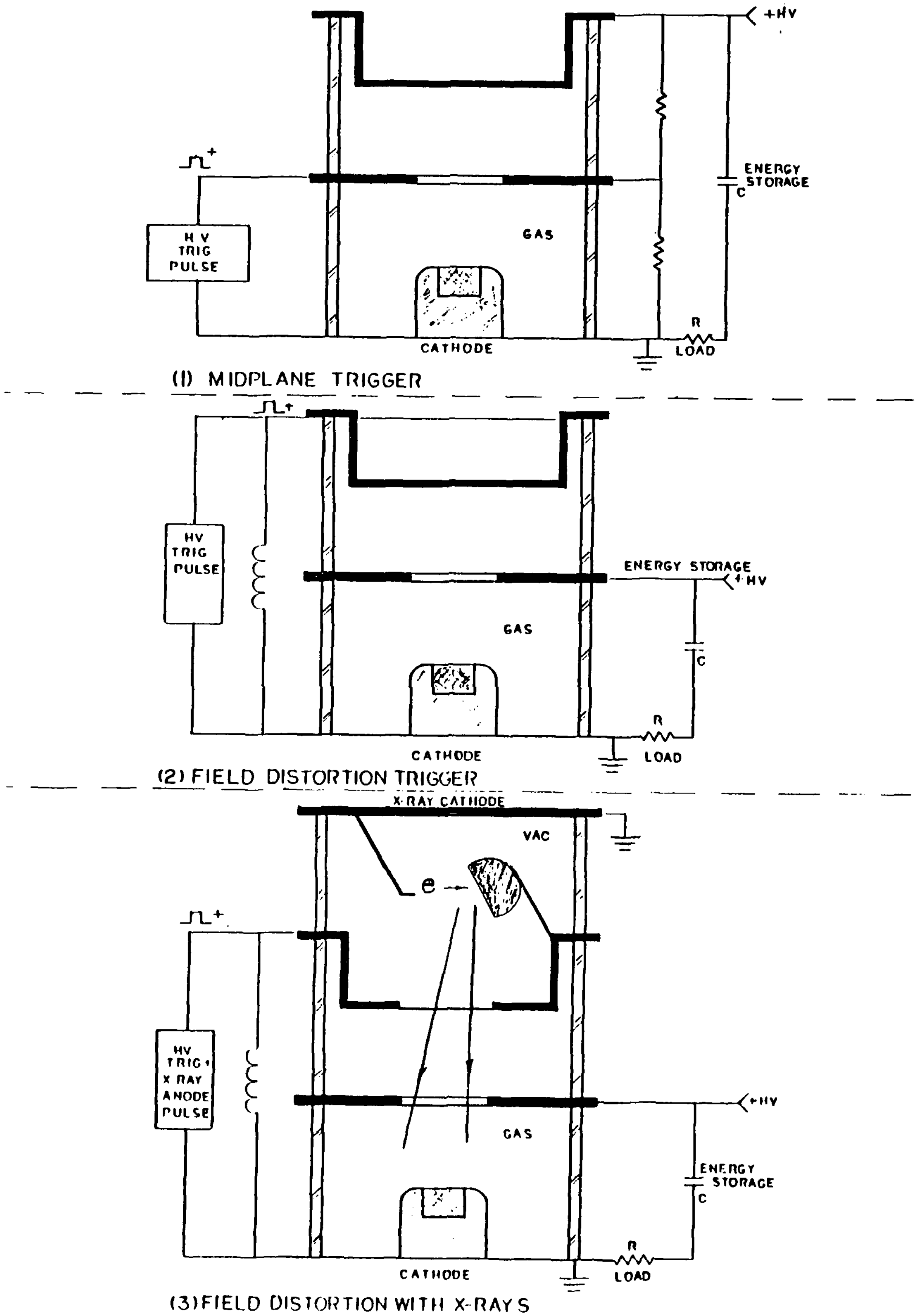
Two methods of triggering the switch were tried. The same electrodes were used, but connected differently to the main discharge circuit and the trigger pulse generator. Figure 5 shows the two arrangements. Both methods essentially trigger the gap by over-volting, in the absence of intense ionization.

The first is to use a mid-plane electrode which is pulsed positive with respect to the cathode. This geometry closely resembles that of many triggered spark gaps.

The second arrangement is to use the "middle" electrode as the anode, and to trigger the device by distorting the field in the main gap. To increase the main gap field, the outermost electrode is pulsed to a high voltage, generally positive since the tungsten cathode must be negative in order to emit. The middle, anode electrode must therefore have a fairly wide opening to permit adequate field penetration. This arrangement also lends itself well to the X-ray pre-ionization structure, in that:

i) The X-ray cathode is permanently grounded, and

ii) The anode is also at DC ground, but is pulsed up positive along with the field distortion trigger, which can be the same electrode. The high voltage insulation problem is thereby minimized.



- FIGURE 5- ELECTRODE CONNECTIONS

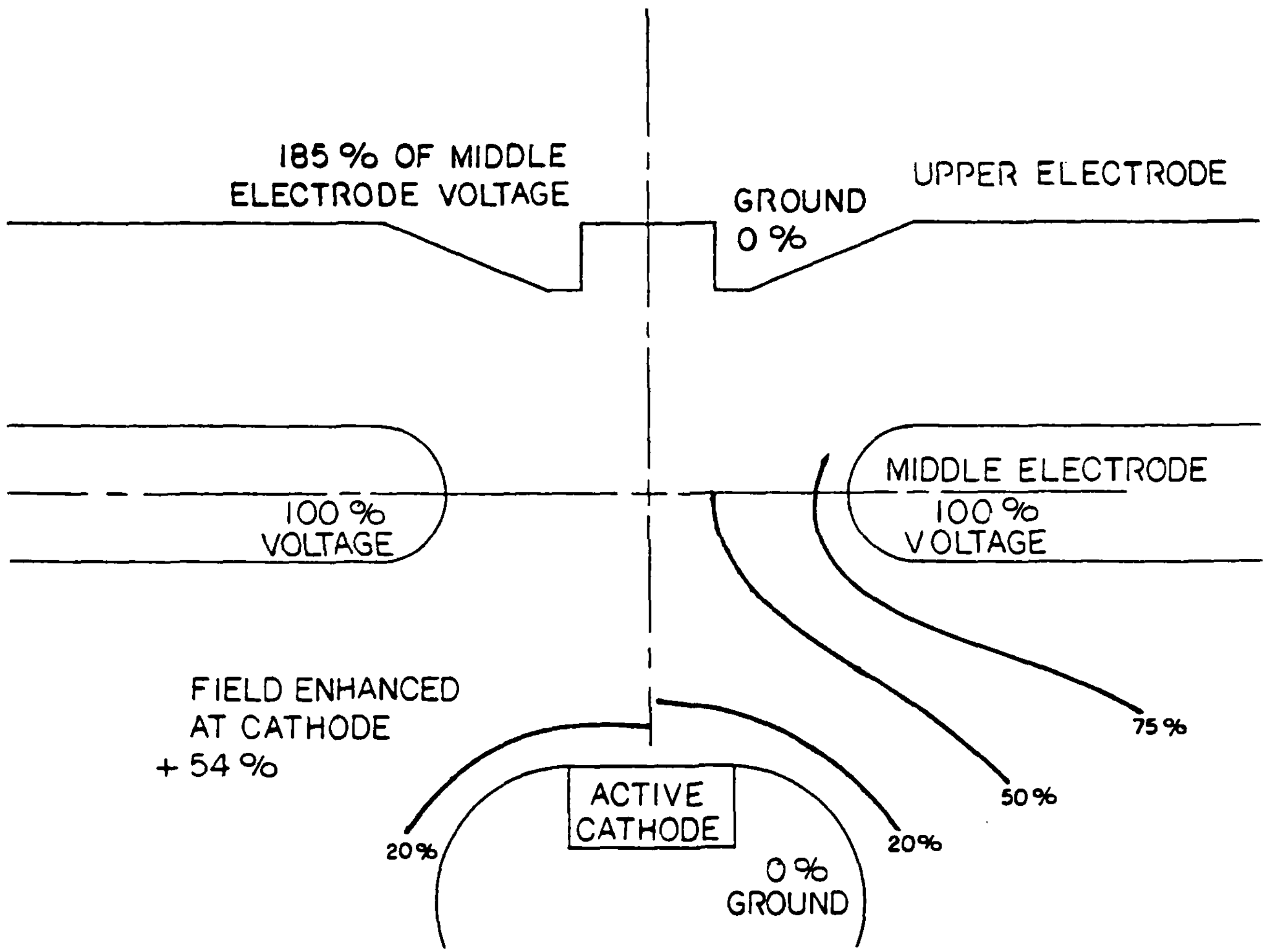
In order to determine an adequate starting point for the electrode shapes, several field plots were made. Since the switch, both in concept and in this experiment was linear, with a 10 cm cathode length, a two dimensional approximation could be used for the electrostatic field plots. A variety of spacings, openings and shapes could be used, as well as other electrodes. Some of the results which led to the final design are shown in figures 6, 7, 8, 9 and 10. It was (as might be expected) difficult to find a suitable compromise between field uniformity and effective trigger field enhancement at the cathode surface. The geometry finally chosen requires large voltages to significantly change the field near the cathode, if the field penetration trigger method is used. This may be expected to give a poor triggering range, and does in practice.

3.3.3 Switch Structure

The final switch structure are shown in figures 11 and 12, one with, and one without the X-ray source. Figure 13 and 14 shows the midplane and outer cathode electrodes, and figure 15 the cathode. The important structural elements are:

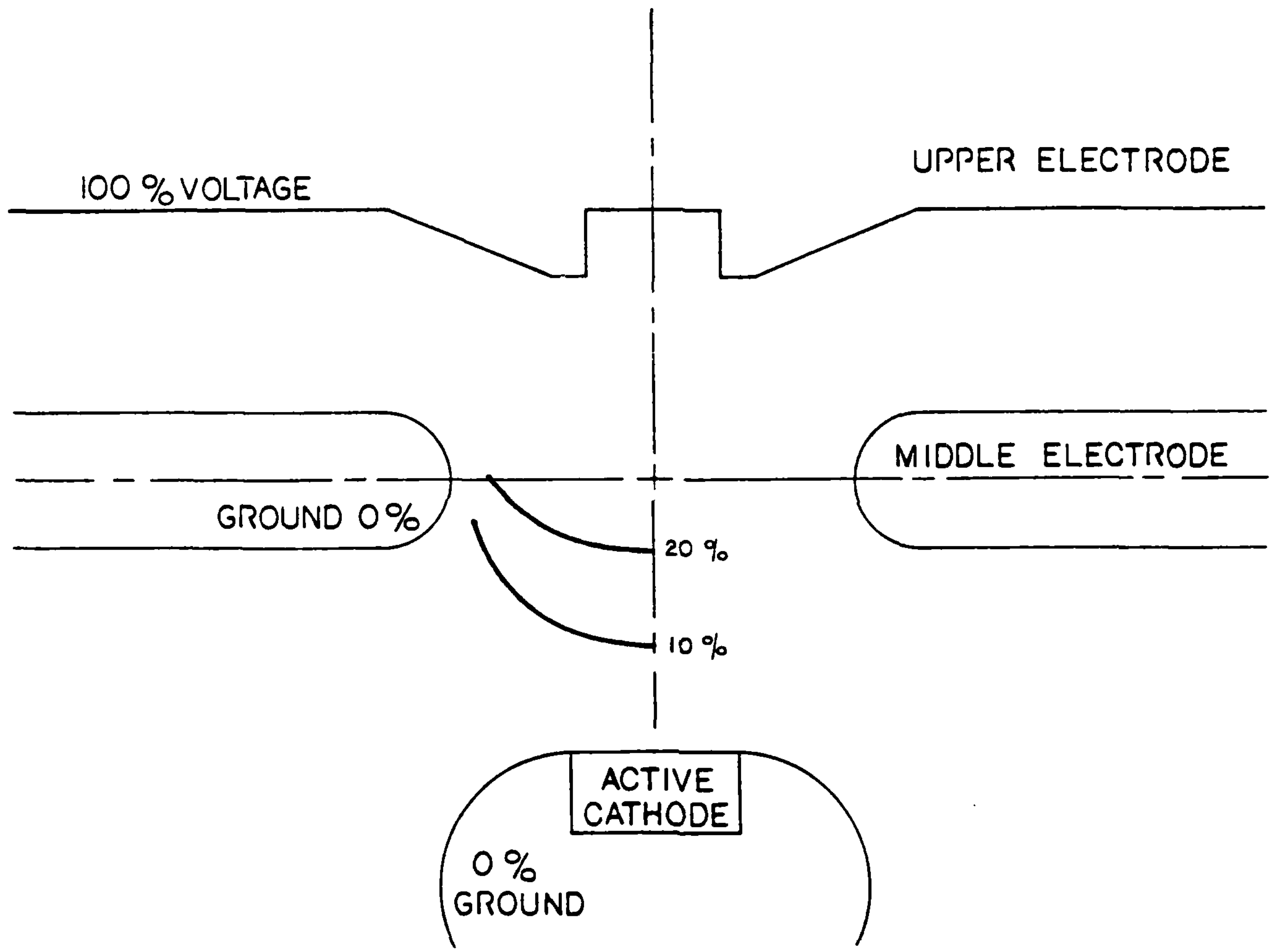
Cathodes	Spectramat Inc., Barium Aluminate impregnated porous tungsten, with heater
Main Electrodes	304 stainless steel
Insulators	Schott 8330 glass, with viton L gasket seals
Cathode Support and Heat Shields	0.010 inch 304 stainless steel

Major problems were encountered with the fabrication of the X-ray source chamber. These problems, mainly due to material contamination, prevented us from achieving a sufficiently leak tight anode seal, and budget and time constraints prevented completion of this portion of the planned work. In spite of this disappointing setback, useful data was obtained for the evaluation of the switch.

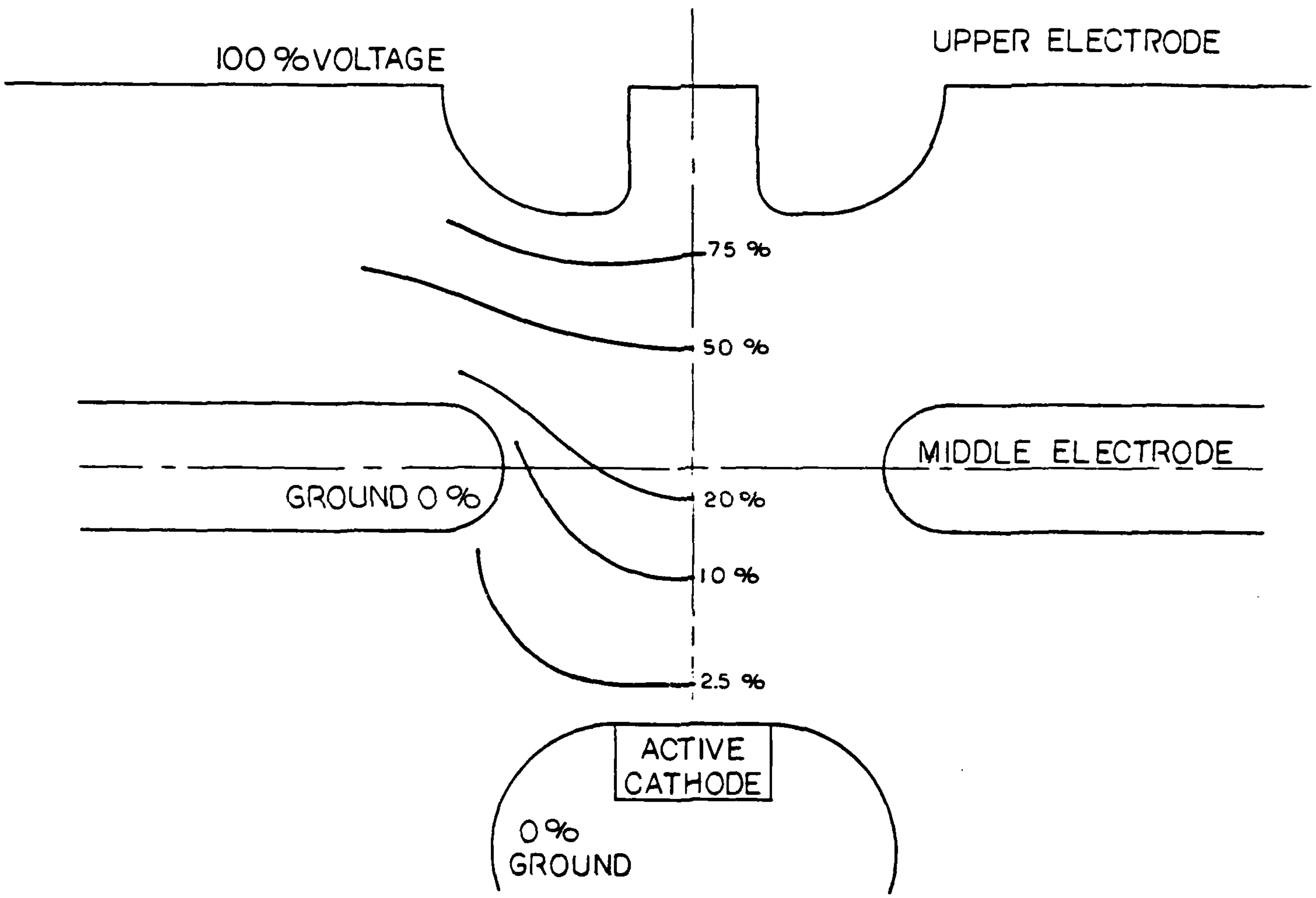


EQUIPOTENTIALS

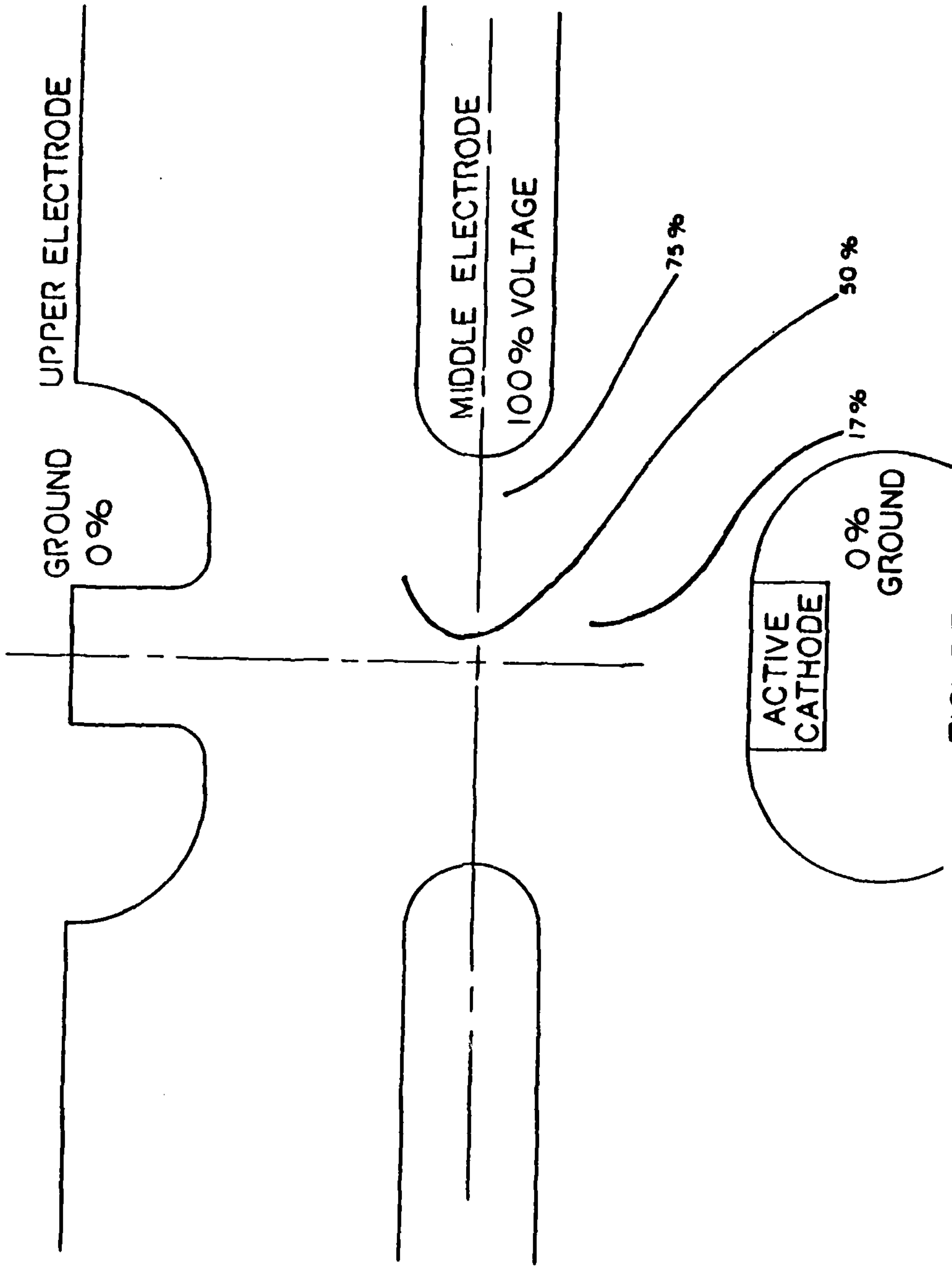
—FIGURE 6—


UPPER ELECTRODE
100 % VOLTAGE
MIDDLE ELECTRODE
GROUND 0%
20 %
10 %
ACTIVE
CATHODE
0 %
GROUND

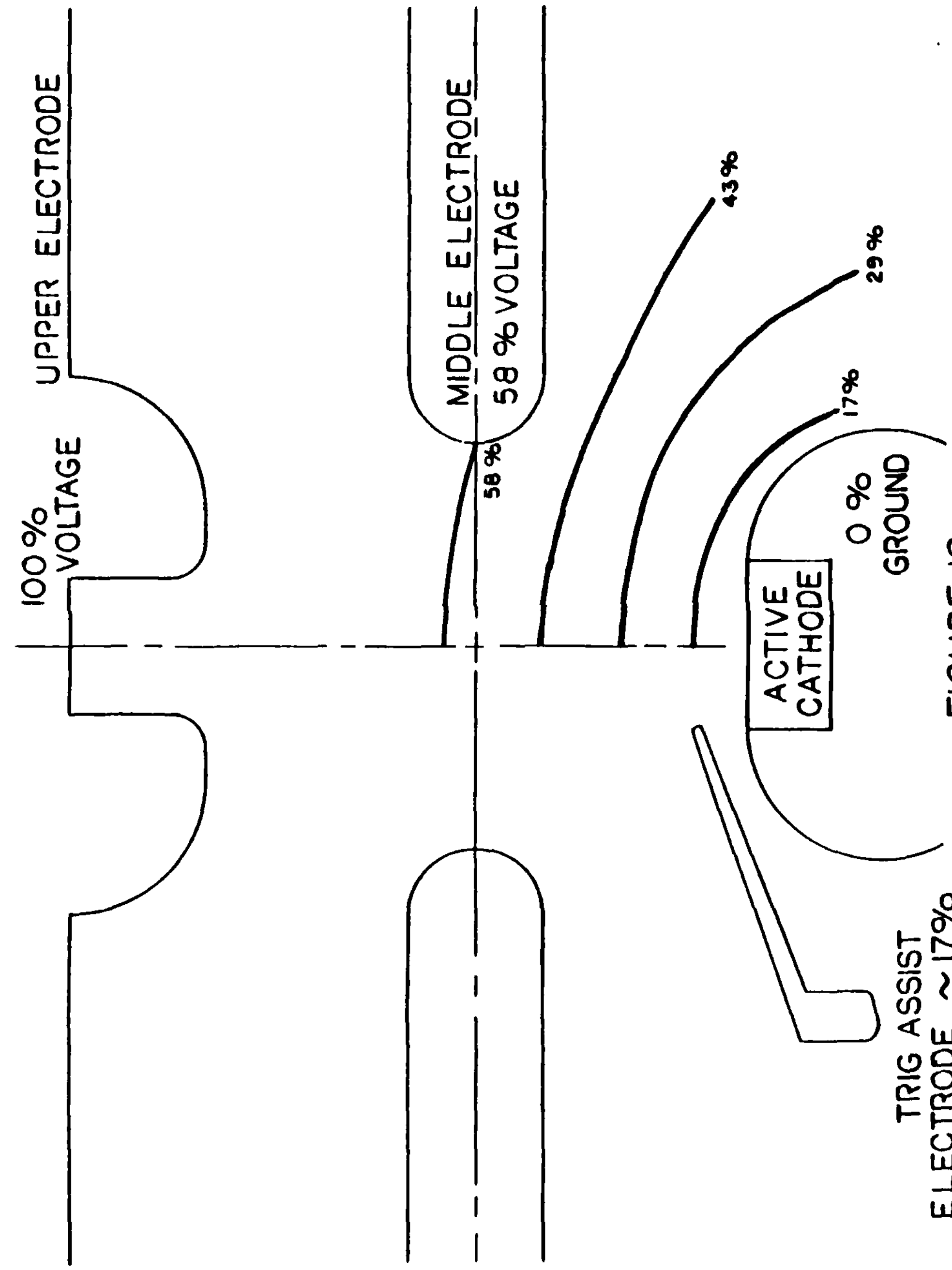
—FIGURE 7—


100 %VOLTAGE
UPPER ELECTRODE
75 %
50 %
MIDDLE ELECTRODE
GROUND 0 %
20 %
10 %
2.5 %
ACTIVE
CATHODE
0 %
GROUND

—FIGURE 8—

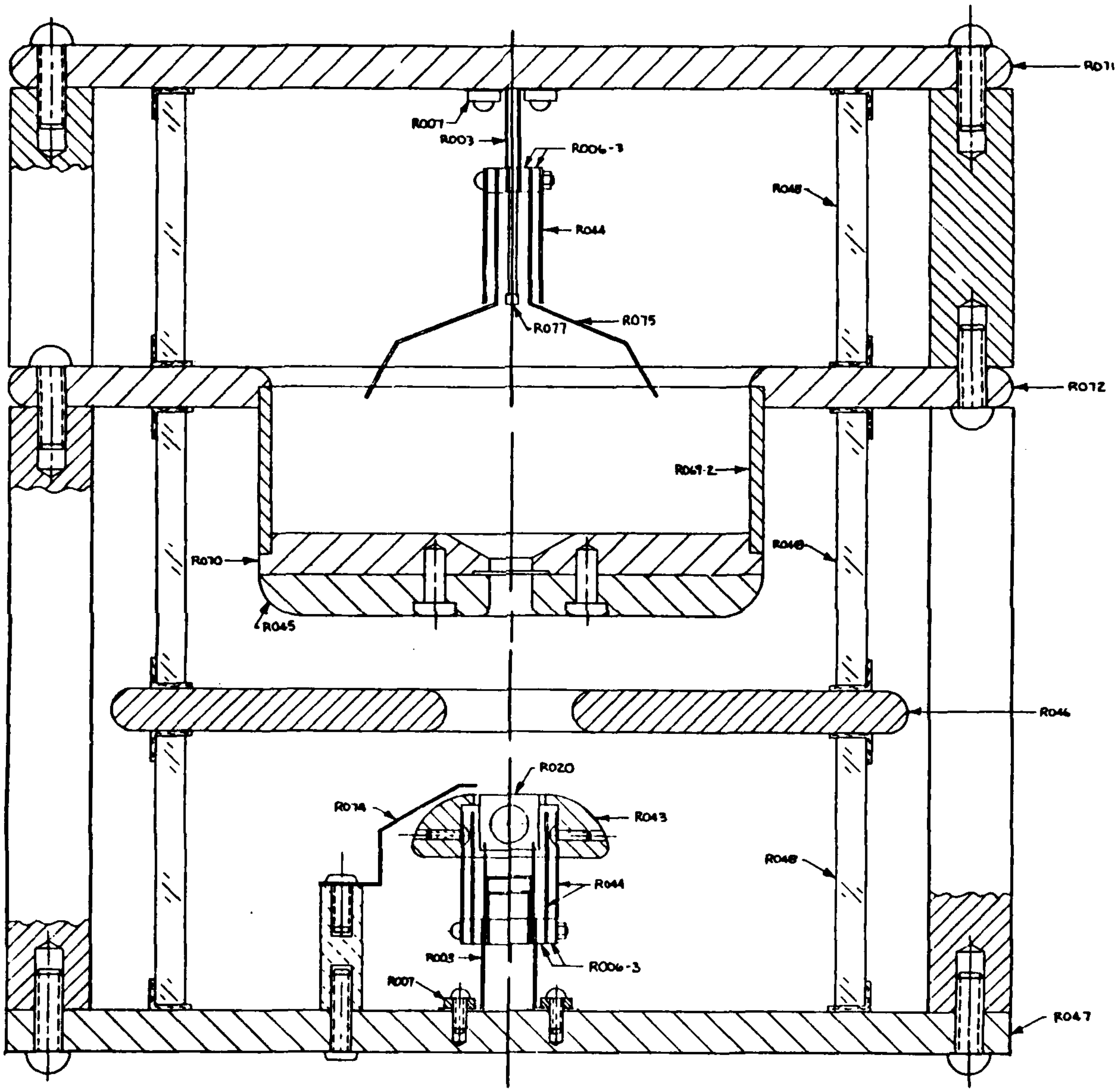

UPPER ELECTRODE
GROUND
0%
MIDDLE ELECTRODE
100% VOLTAGE
75%
50%
17%
0%
GROUND
ACTIVE
CATHODE

— FIGURE 9 —



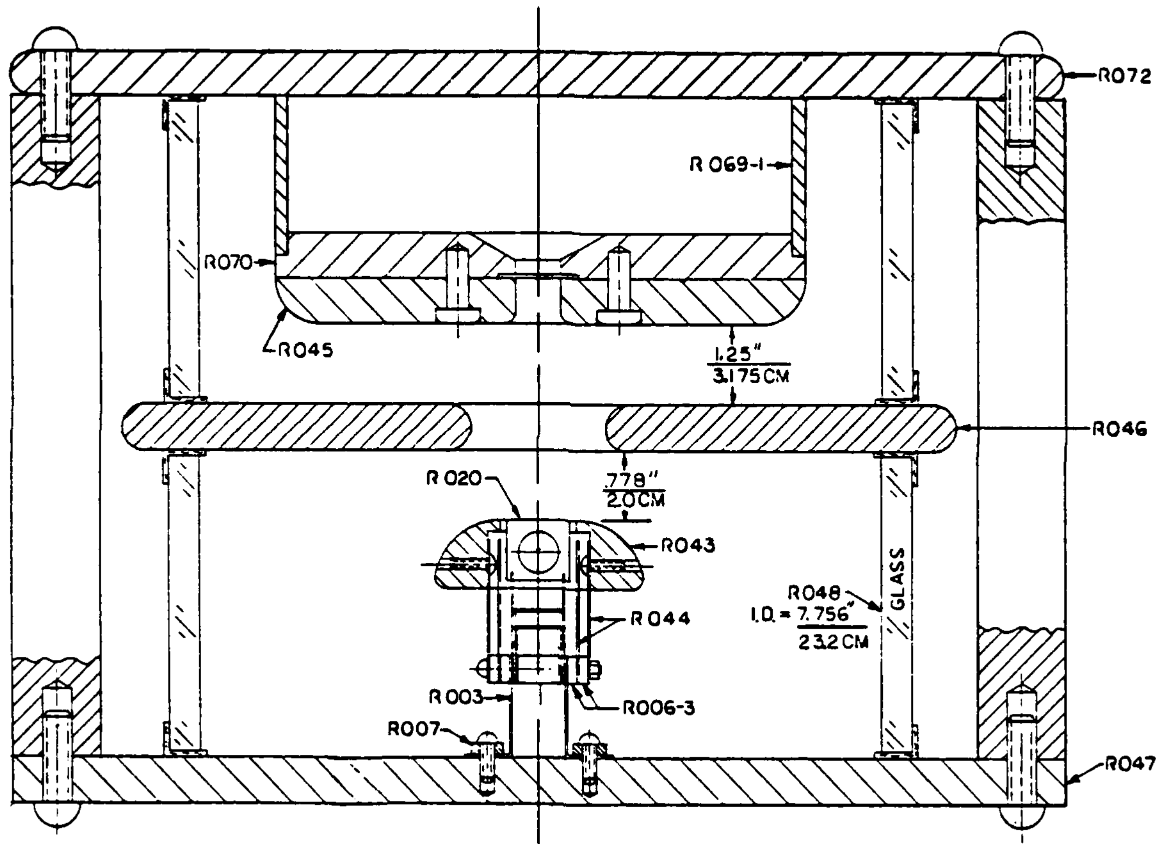
UPPER ELECTRODE
100 % VOLTAGE
MIDDLE ELECTRODE
58 % VOLTAGE
58 %
43 %
29 %
17 %
0 %
GROUND
ACTIVE CATHODE
TRIG ASSIST ELECTRODE ~17%

— FIGURE 10 —

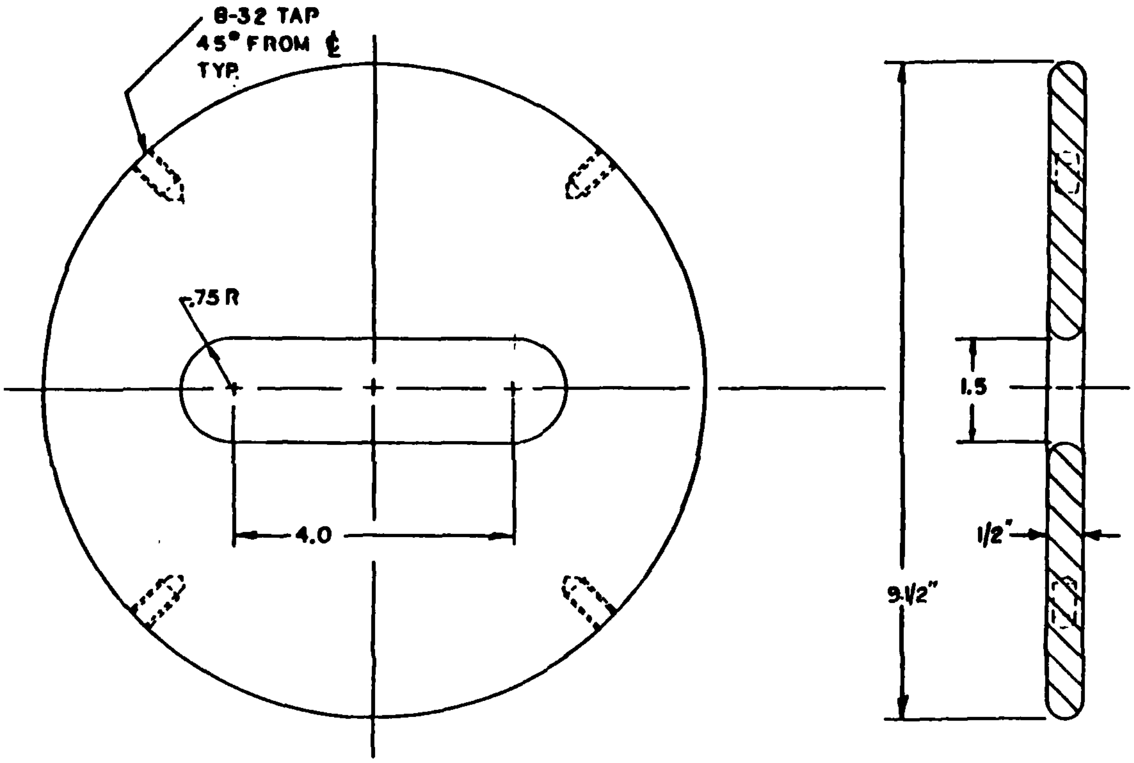


—FIGURE 11—

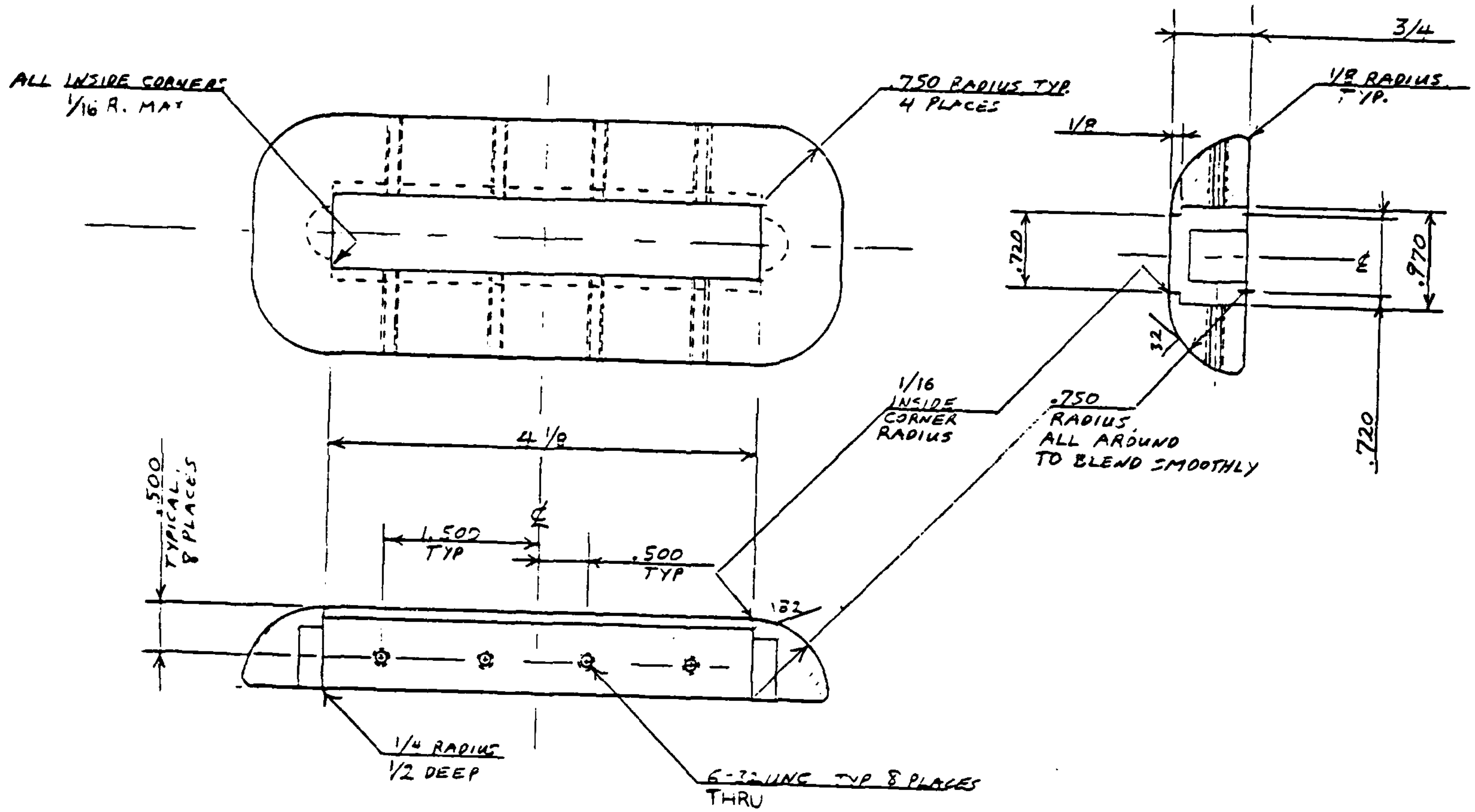
SWITCH WITH X-RAY PRE-IONIZER



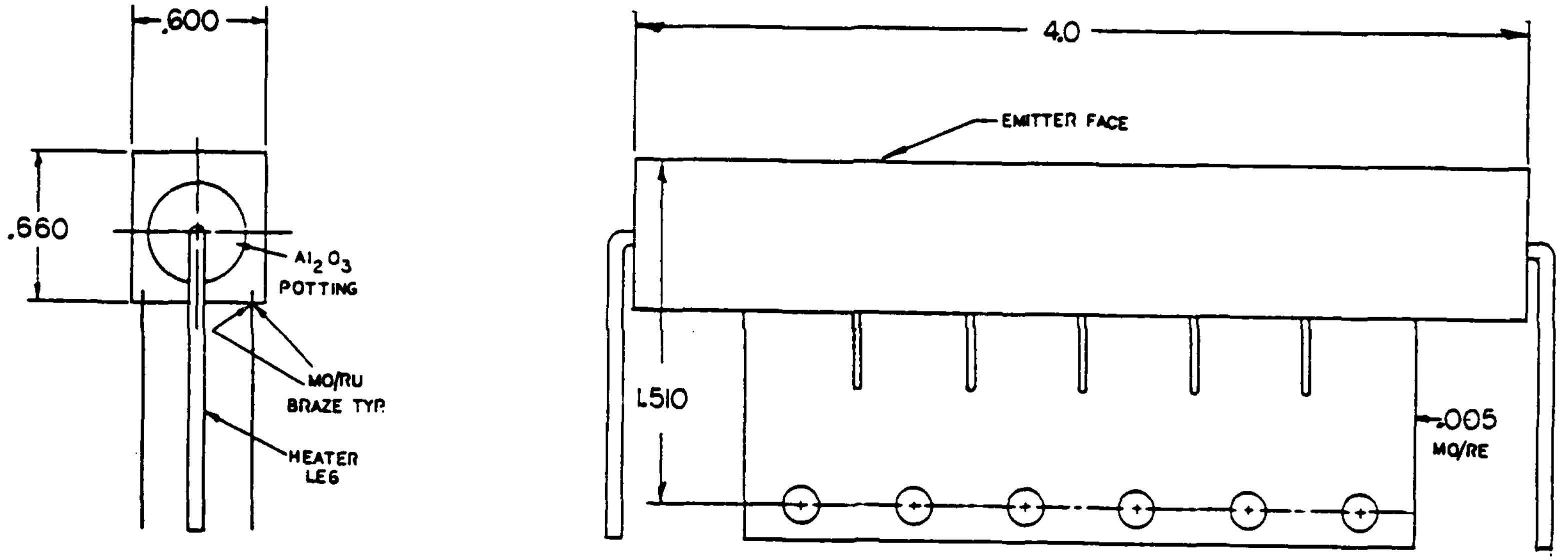
— FIGURE 12 —
EXPERIMENTAL SWITCH



—FIGURE 13—
MIDPLANE ELECTRODE



—FIGURE 14—
OUTER CATHODE ELECTRODE



—FIGURE 15—
DISPENSER CATHODE

4. EXPERIMENTAL RESULTS

4.1 Apparatus

The switch tube shown in figure 12, 13, 14 and 15 was used in both triggering modes. The circuit elements used are listed below:

Energy Storage Capacitor	0.26, 0.52, 1.04 and 2.08 uF
Load Resistance	5 ohms or 0
Main Power Supply	0 to 100 kV
Trigger generators	Impulse Engineering TG40, 0-40 kV, 2 us width, 750 ns rise, 7K source impedance
	Impulse Engineering TG100, 0-70 kV, 2 us width, 15K source impedance. Without sharpening gap: 750 ns rise With sharpening gap : 20 ns rise

Current measurements were made with both a Pearson CVT, and with an 0.01 ohm CVR built for the purpose. The current measurements were reconciled with stored coulombs and discharge time measurements.

Pressure measurements were made with a Wallace-Tiernan Gauge, over the experimental range of 50 to 750 Torr.

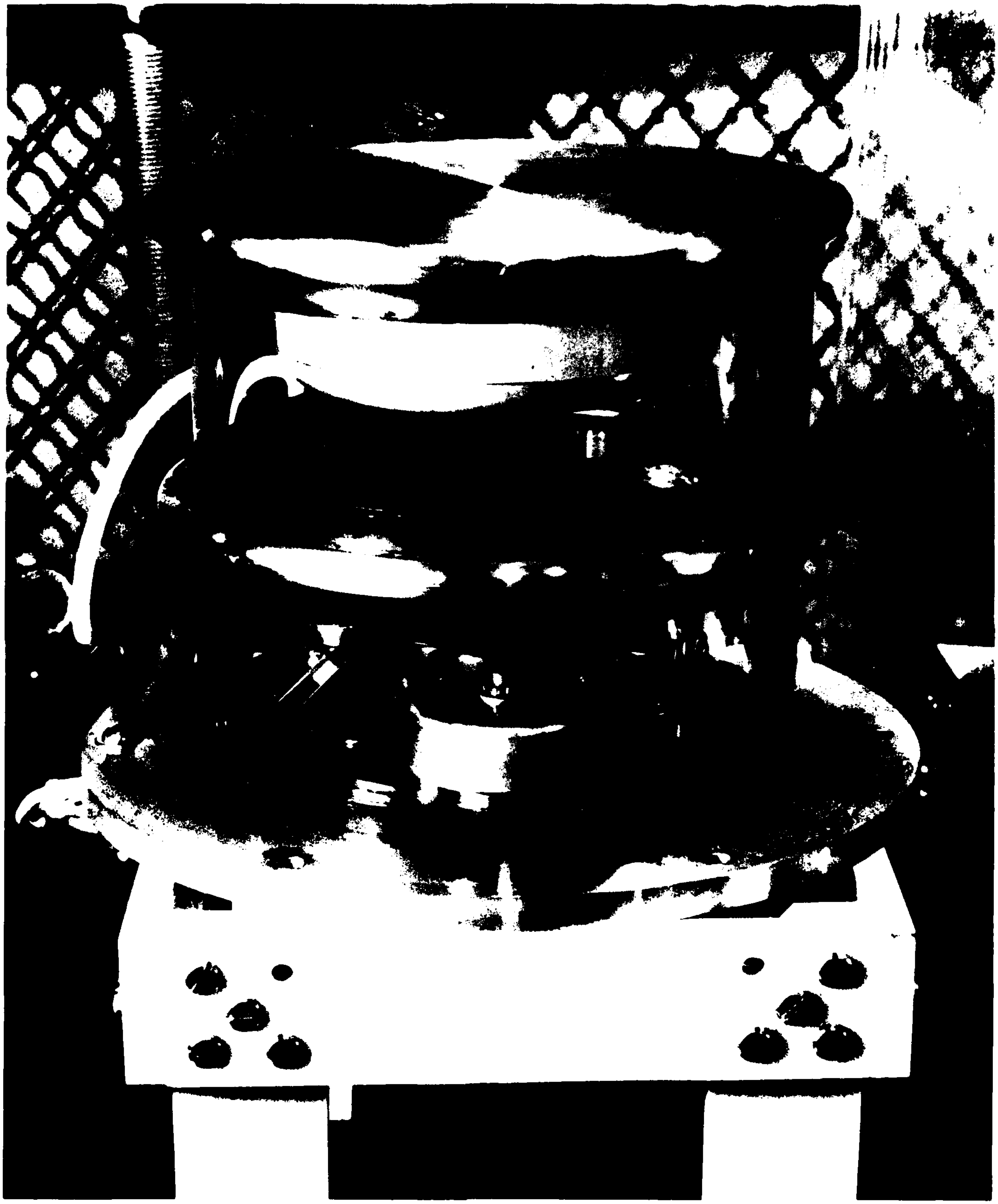
Figures 16 and 17 show photos of the apparatus itself, attached to the diffusion vacuum pump system and gas manifold.

4.2 Test Results

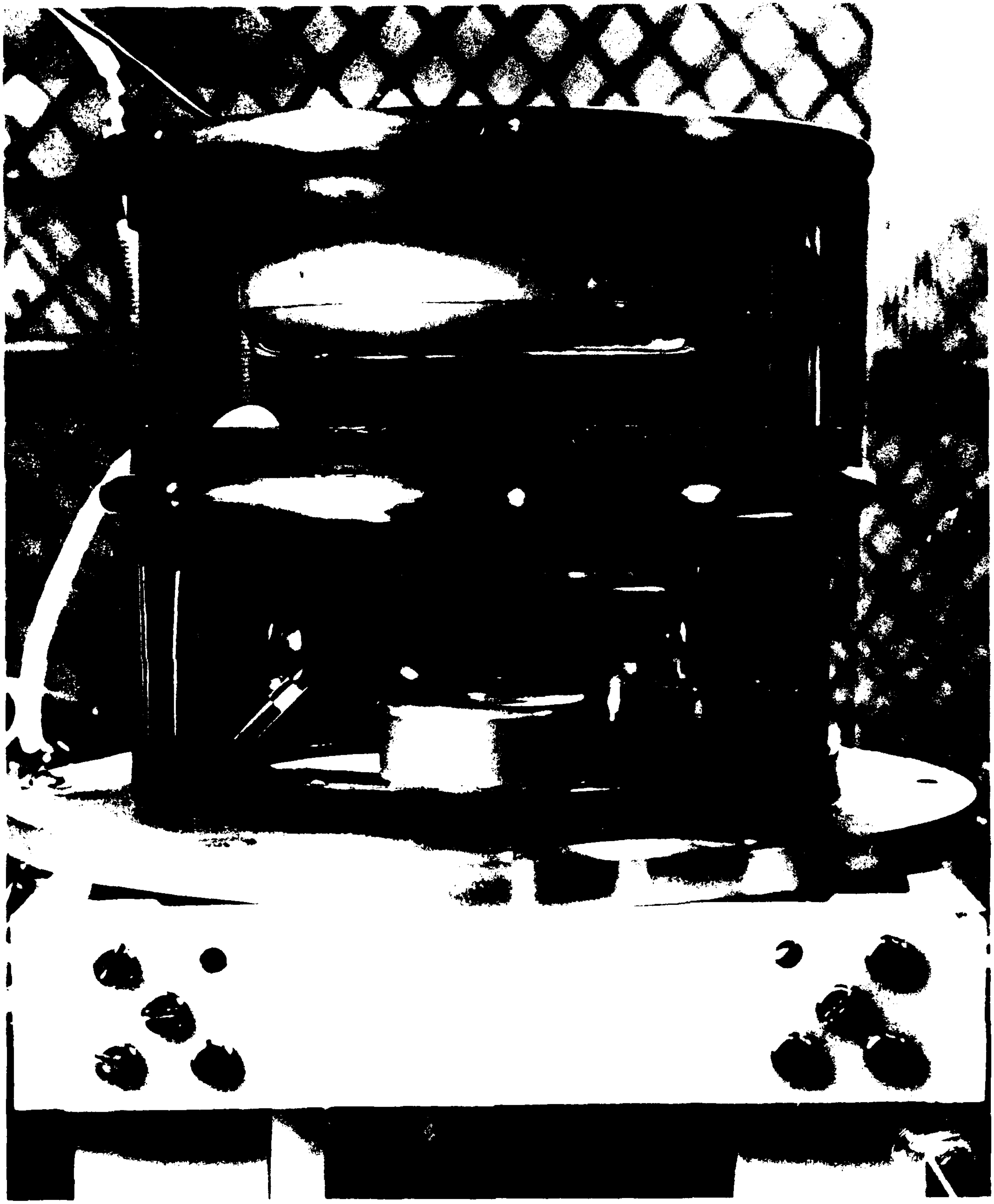
Using the device of figure 11 a series of tests were run with various circuit configurations and polarities. All of the tests used the same gas - 75% Hydrogen and 25% Argon. Pressure was varied over the range of 50 Torr to 750 Torr, just below an atmosphere.

<u>Static Breakdown Voltage</u>

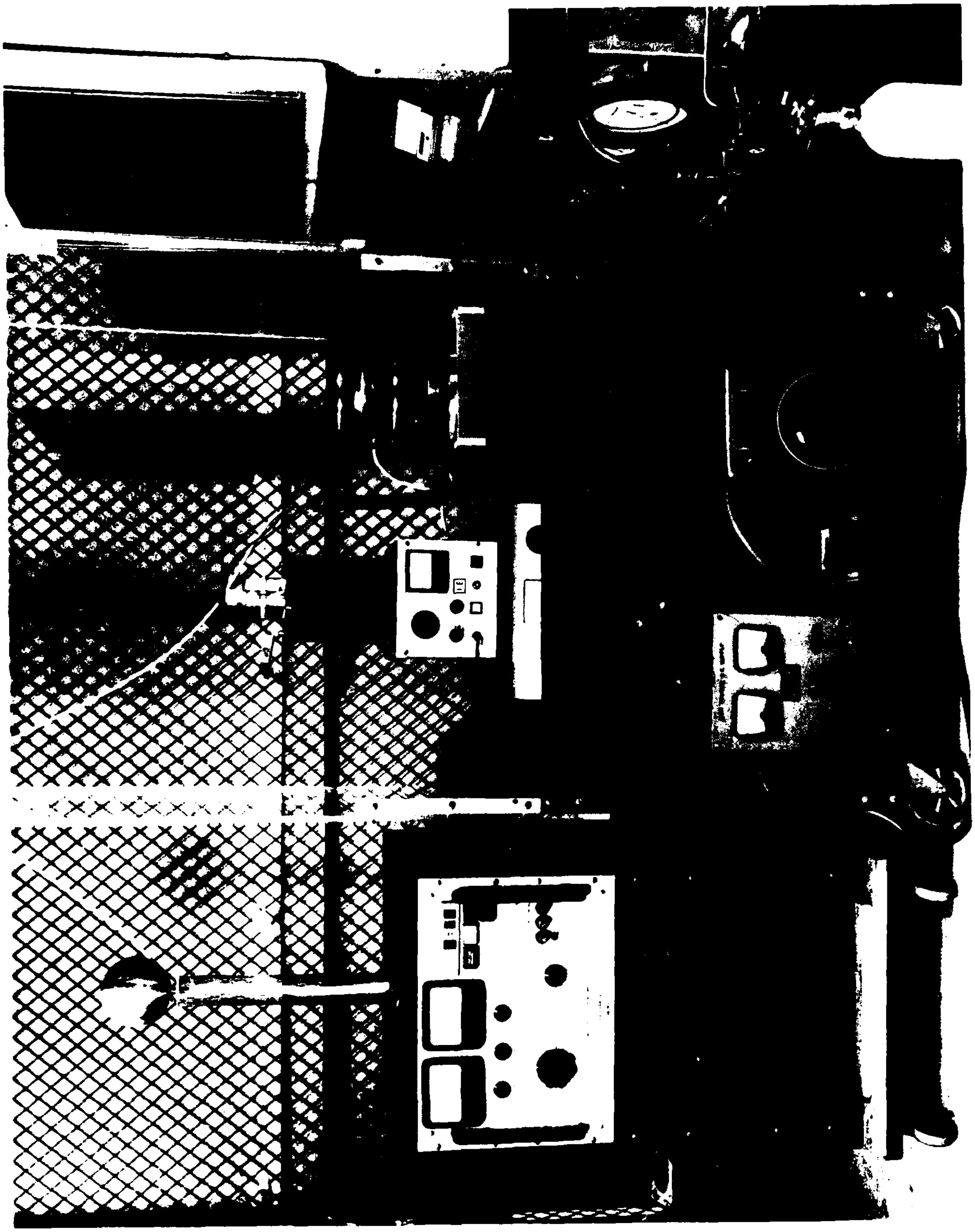
Static breakdown was measured with the upper electrode connected to the middle electrode, and with the middle electrode divided, 50 megohms: 50 megohms, between the upper anode and the cathode. With (first order) total electrode spacings of 2.0 cm and 5.2 cm respectively, the breakdown measurements agree very well with the published data for hydrogen. The 25% Argon does not appear to have changed the breakdown at all. The results are plotted in Figure 1.



EXPERIMENTAL APPARATUS



EXPERIMENTAL APPARATUS



EXPERIMENT TEST STAND

Heating the cathode has a dramatic effect on the SBV, however. With a cathode temperature of 835 °C, at 700 Torr, the upper electrode to cathode SBV falls from about 60 kV down to 22 kV. The reduction is typical, to about 35% - 36% of the value with a cold cathode. The effect is not due to a reduction in molecular density by gas leaving a hot tube for the colder pump manifold; valving off the manifold first doesn't change the effect. In any case, the experimental device has a volume of about 300 cu inches, whereas the manifold volume is less than 5 cu inches. The reduction in SBV might, then, be due to:

1. Electron emission from the cathode, or

2. Local gas density reduction in the immediate vicinity of the hot cathode.

The effect is less at reduced cathode temperatures, but was not tabulated due to temperature measurement limitations. Our means of measuring cathode temperature was with a L&N optical pyrometer, which is ineffective below 800 degrees.

Triggering

Various triggering circuit connections and polarities were tried, with hot and cold cathodes, and with pressures usually between 100 and 700 Torr. Voltage were varied between 5 kV and 40 kV, with many of the tests between 15 kV and 22 kV.

Over the range of experimental variables of pressure, voltage, polarity and circuit connection, the results were consistent, and generally very much the same.

The first series used no form of pre-ionization. The results are summarized below.

Multichannel Discharges

Multichannel discharges were formed under one condition. The stored energy was low, with 0.1 to 0.4 joules in 6600 pF at 5 kV to 10 kV, connected to the middle electrode. The trigger pulse of 40 to 50 kV was applied negative to the upper electrode, forming one to several weak streamers. The main discharge would take place as 2 or 3 dozen thin blue (molecular H2) channels to the edges of the cathode along the entire 10 cm length. Pressure was varied from 250 to 500 Torr with no change. An increase in voltage or capacitance caused the end of the multiple channels, and the formation of one intense red arc channel. A change to a positive trigger has the same effect.

Trigger Rise Time

All of the various trigger effects were found to be insensitive to the rise time of the trigger, using the two different trigger generators and with trigger rise times of either 3/4 usec, or 10 to 20 nsec with the trigger sharpening gap. In no case did the use of a fast rise cause any observable difference in anode delay time, anode voltage fall, or discharge channel appearance.

Minimum Anode Voltage

With the middle electrode triggered, (Figure 5A) the upper electrode as anode, and a 70kV fast rising trigger, the minimum anode voltage at which the device triggers is 50 to 60% of the self breakdown voltage.

With the upper electrode triggered (Figure 5B) and the middle electrode as anode, the minimum anode voltage for triggering is very high, usually 80 t0 90% of self breakdown.

Channel Formation and Spread

With the cathode cold, the discharge would always form as a fairly concentrated channel from an electrode edge to the cathode edge. If the midplane is triggered the discharge forms as two separate arcs - cathode to midplane and midplane to anode. Figure 18A shows this behavior and contrasts it with the behavior with a hot cathode.

With a hot cathode the discharge formation is very different:

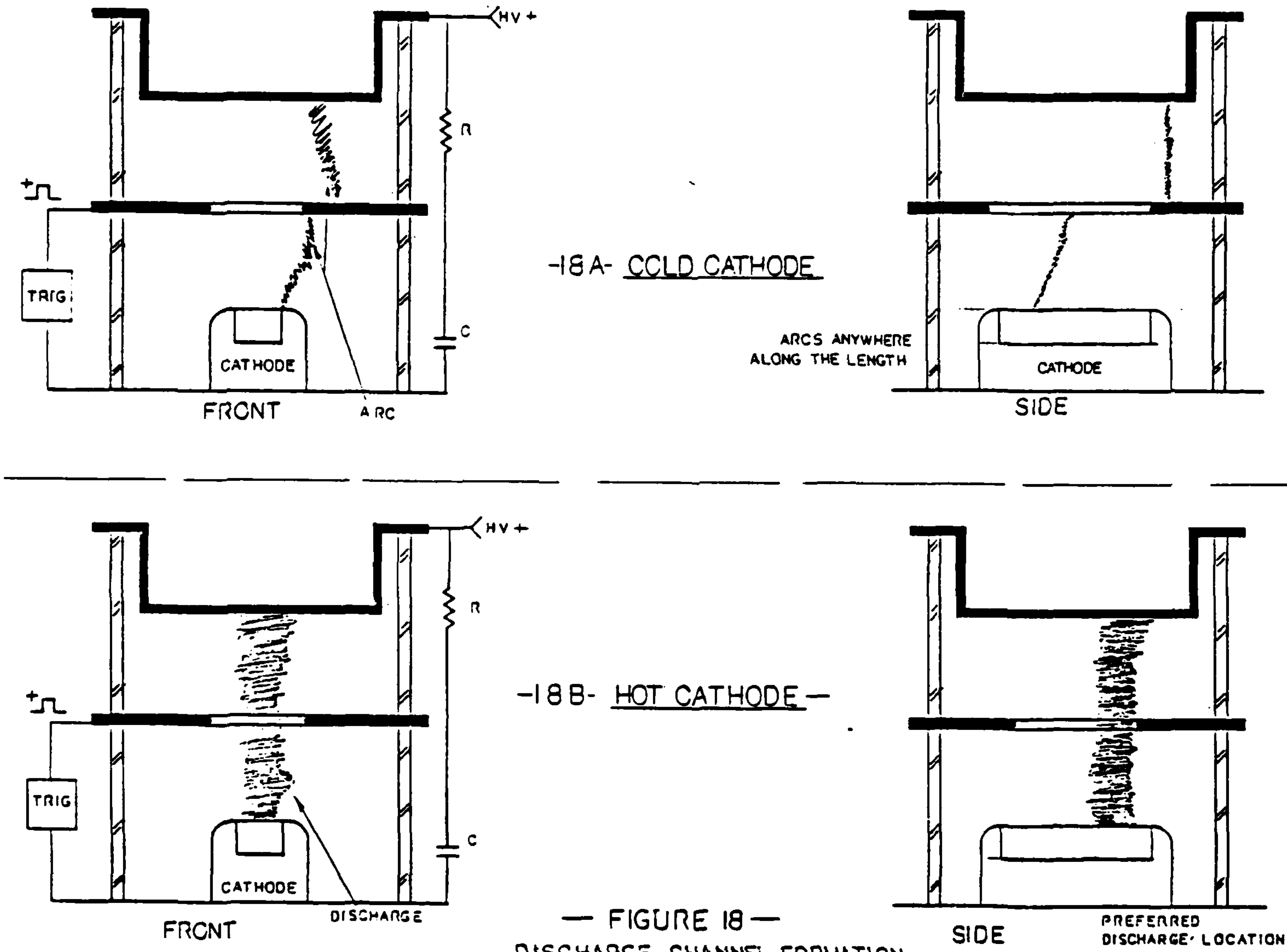
1. The channel forms indirectly from cathode to anode, in a preferred location. Figure 18B illustrates this behavior.

2. The discharge column is larger for larger peak currents. The size of the column is estimated.

Discharge Capacitance (uF)	Load Resistance (ohms)	Peak Current (amps)	Discharge Column Diameter (approximate)
2.08	0	16,100	1-2 cm
1.04	5	3,400	1/2 cm
1.04	5	<1000	narrow channel

3. The initial tests in which this behavior was seen were done with a cathode temperature of 820 - 840 degrees C, with a heater input of 6 volts and 36 amps.

Reduction of the heater input to 4 volts and 27 amps gives the same result, but at an unknown cathode temperature (the cathode is dark). At still lower heater power the "activity" stops; that is, the device acts as if cold, at room temperature.



— FIGURE 18 —
DISCHARGE CHANNEL FORMATION

Commutation Delay and Anode Fall

After trigger breakdown, the sequence of events in the switch are:

1. Commutation delay, with the discharge developing in a high impedance state, the anode voltage only slightly below its pre-triggering value. This pre-conduction state is often observed in gas discharges of all kinds, including switches. In many devices this period lasts for only a few nanoseconds as a "front porch" on the pulse.

2. Anode fall time, the "resistive" portion of the switching, with the voltage falling to its low, full conduction value, and with the current rising but limited by the switch impedance. In most of the gas discharge switches this time is found to be a strong inverse function of the pressure. Typical values are:

Device	Pressure	Fall Time Magnitude
Vacuum Gaps and Ignitrons	.001 Torr	1/2 usec
Thyratron	.2 -.5 Torr	20-50 nsec
Spark Gap	500-200 Torr	1-5 nsec

3. Conduction period, with the anode voltage low, a few hundred volts, and the current (and its rise) limited by the external discharge circuit.

In this device the commutation delay and anode fall were anomalously long.

First, the commutation delay was never less than 1/2 - 1 microsecond, and was sometimes as long as several hundred microsesonds. Even with anode voltages within 80 to 90% of self breakdown, the typical commutation delays were 1 to 10 usec, over the entire 100 to 750 Torr range. There was always considerable shot-to-shot variation in the delay, and also in the magnitude of current flow during this time. The current flow was surprisingly high -- often currents of 200 to 400 amps would flow for a microsecond before the switch would begin to collapse. Altogether the commutation delay in this device was characterized by

Commutation delay times	- 1/2 to 500 usec
Shot-to-shot time variation	- 1 to 5 range
Pre-breakdown currents	- up to 400 amps

A further unexpected finding was that the commutation delay of 1/2 - 1 usec and currents of several hundred amps were present even during self-breakdown.

The anode fall time was also long - 0.1 to 0.5 microseconds, also with shot-to-shot variation. These unmistakably slow fall times were an order of magnitude longer than expected, based on other types of switches. The pressure, voltages, or other variables were not observed to significantly affect either of these two critical switching times.

Pre-Ionization by Sparker

Since the X-ray pre-ionizer could not be completed for this first phase, a simple sparker pre-ionizer was used. The sparker was a single probe in the center of the upper electrode. The spark from the probe to the adjacent portion of the upper electrode plate was shielded electrostatically by the re-entrant portion of the upper electrode, but could illuminate the active volume of the device through the 1/2 x 4 inch slot in the electrode. This slot was, of course, aligned with the middle electrode slot and the cathode.

The sparker current was typically a 2 microsecond 1/2 sine (with about 25% reversal) of 5 to 7 amps peak.

Again, triggering was explored over a 100 to 600 Torr region at 8 to 30 kV, with a fast rising trigger, and hot and cold cathode. No significant effect could be found on minimum anode voltage, commutation delay and jitter, or fall time. This lack of effect from the weak ionization produced by the sparker is only to be expected in a device with hundreds of amps of pre-breakdown current.

5. CONCLUSIONS AND RECOMMENDATIONS

Preliminary studies of a high voltage switch concept using a high pressure gas and an active, non-arcing cathode, have been completed. The parameters of the experiment were:

Electrode spacings	2-5.2 cm
Gas	75% H2 + 25% Ar
Gas Pressure	50 to 750 Torr
Cathode Electrode	Barium Aluminate impregnated tungsten
Cathode Temperature	20 to 840 degrees C
Anode Voltages	0 to 40 kV
Trigger Voltages	25 to 70 kV
E/P	15 - 22 V/cm/Torr
Anode Currents,(peak)	500 - 20,000 amps
Current Pulse Widths	1 - 20 microseconds

The conclusions from these experiments are:

1. The gas used is not suitable for a switching application, even though it may be very good for SBV stability and cathode chemistry. The long commutation delays and very high jitter are not suitable for pulse switching in the microsecond regime, and out of the question in the 50 or 100 us region.

2. The heated, active cathode (and gas?) does result in discharge spreading, although with current densities of several thousand amps per sq. cm. When the cathode was hot - at least in excess of 4 or 500 degrees C, increasing current caused increasing utilization of the cathode and anode areas. This switch does not arc in the normal sense.

3. Intense pre-ionization might improve the discharge uniformity, but it is unlikely that any reasonable amount of pre-ionization would correct the unacceptable trigger behavior.

Since the behavior of the switch with a slightly heated cathode shows that the concept may have some validity, we do not recommend that this approach be totally abandoned. The active cathode does, indeed, prevent the formation of the usual, very high density, destructive arc spot. The trigger delay problems seem to be associated with the gas.

It is recommended that any further action taken with this type of switch:

1. Concentrate initially on the gas fill used, to obtain good switching characteristics compatible with the cathode natural. Other predominately rare gas mixtures may be more suitable.

2. Examine the suitability of the switch for use with longer current pulses - several microseconds or more.

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